United States Patent

Widmayer

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[54] ELECTRIC CURRENT CONTROL APPARATUS

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[52] **U.S. Cl.** .....**315/107,** 307/297, 315/100 H, 328/76

[51] **Int. Cl.** **H05b 39/04**

[58] **Field of Search** .....328/270, 269, 76, 210; 315/100 H, 252, 340, 307, 107, 106, 94, 97; 307/297

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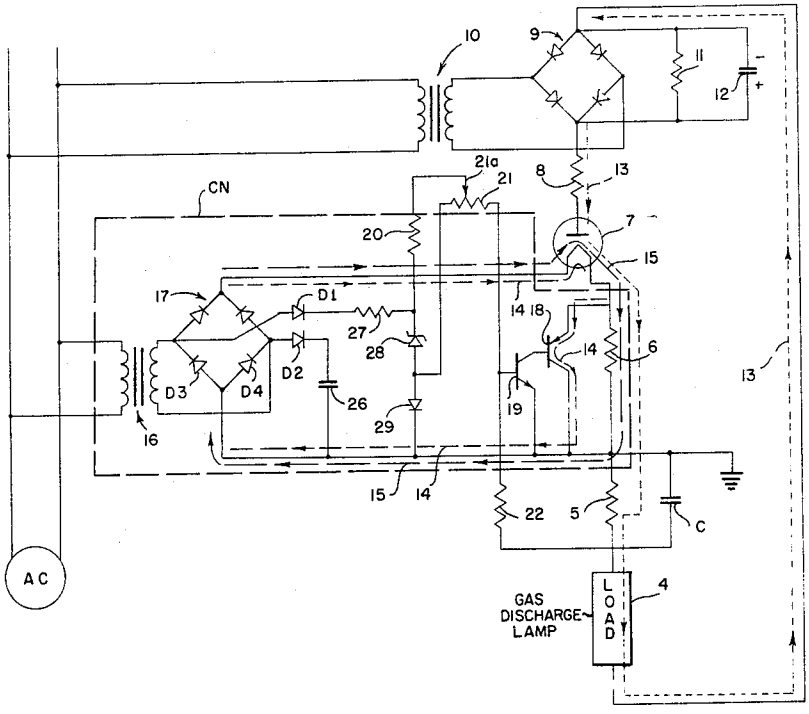
[57] **ABSTRACT**

A current control system particularly useful but not limited to high voltage non-linear load devices wherein a vacuum tube, connected in series relationship with the load device and a DC power source, is operated in a controlled electron emission mode. The current through the load may thus be controlled by controlling the current flowing from the anode to the cathode of the vacuum tube.

10 Claims, 8 Drawing Figures



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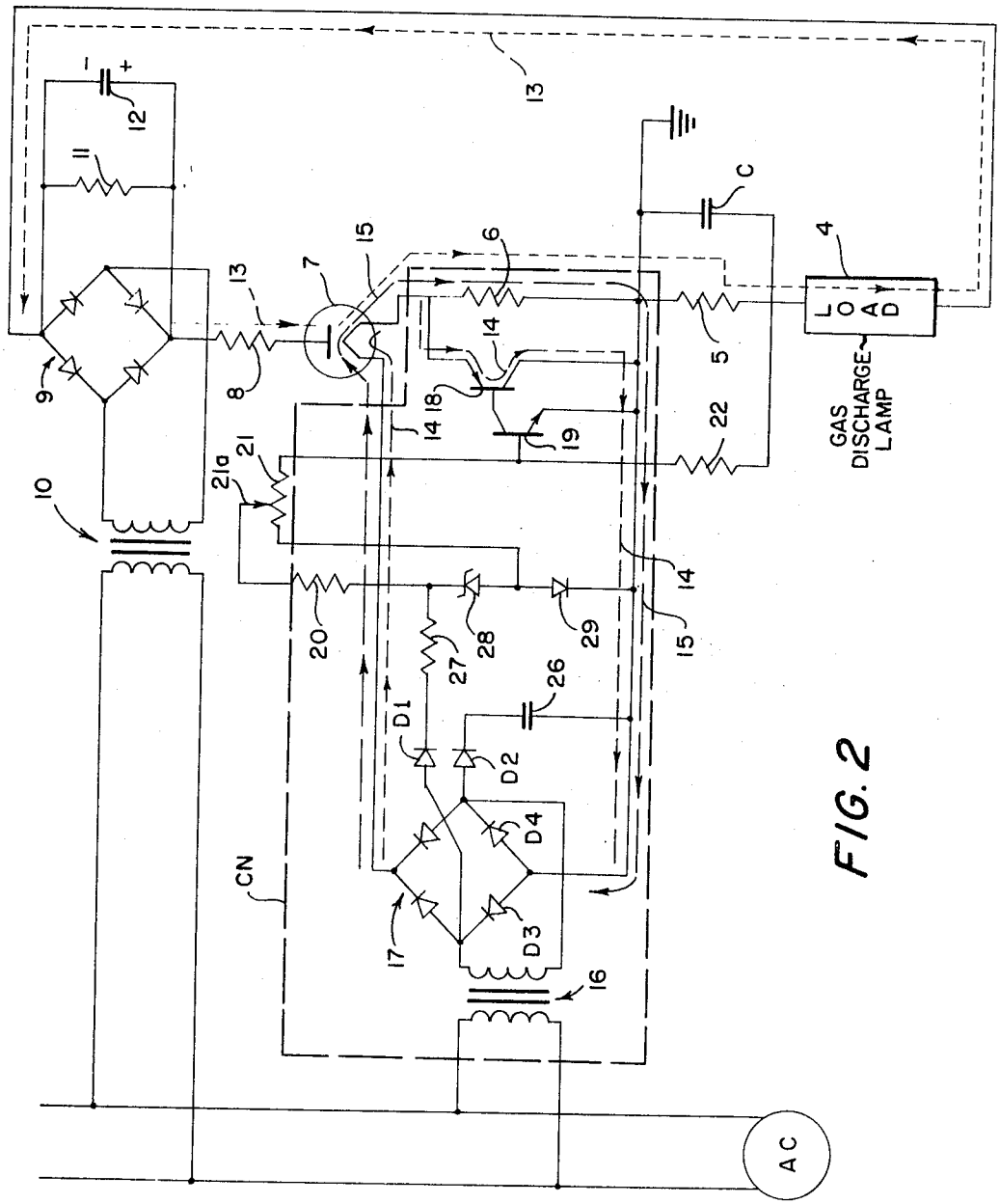

FIG. 2

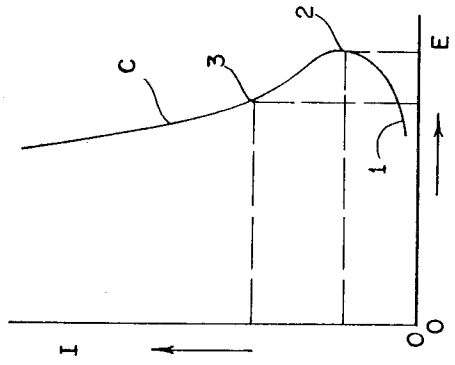

FIG. 1

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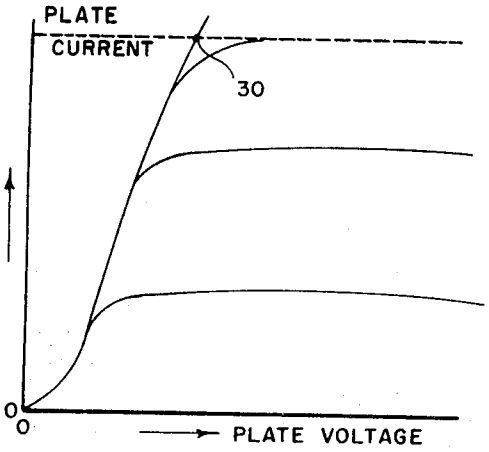

FIG. 3

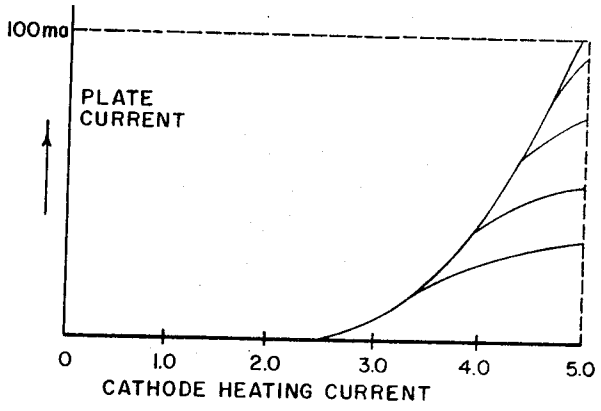

FIG. 4

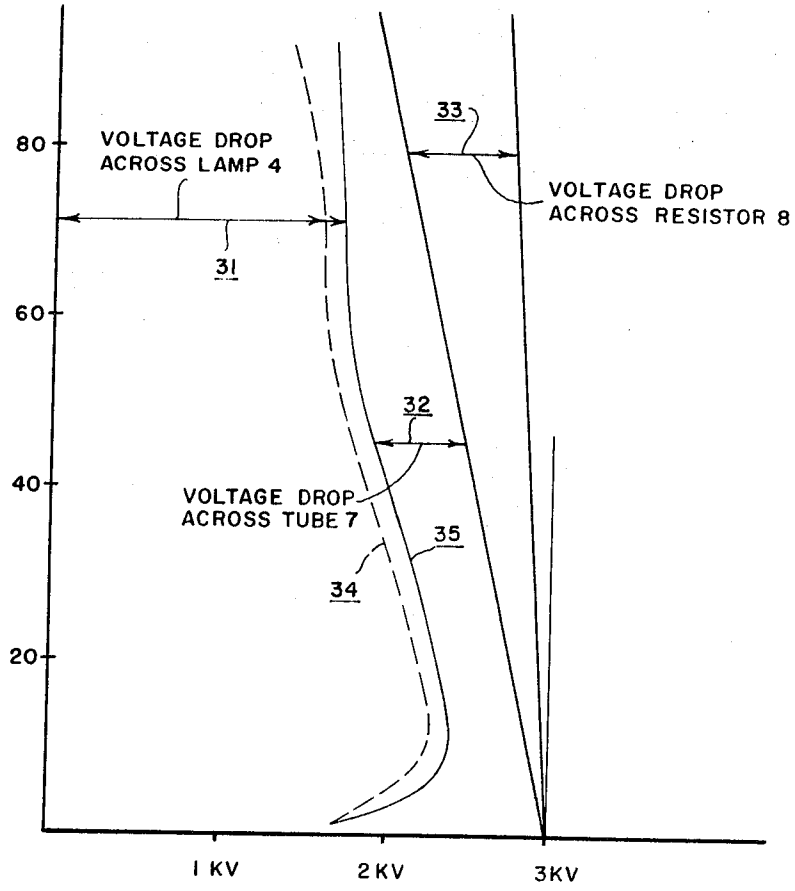

FIG. 5

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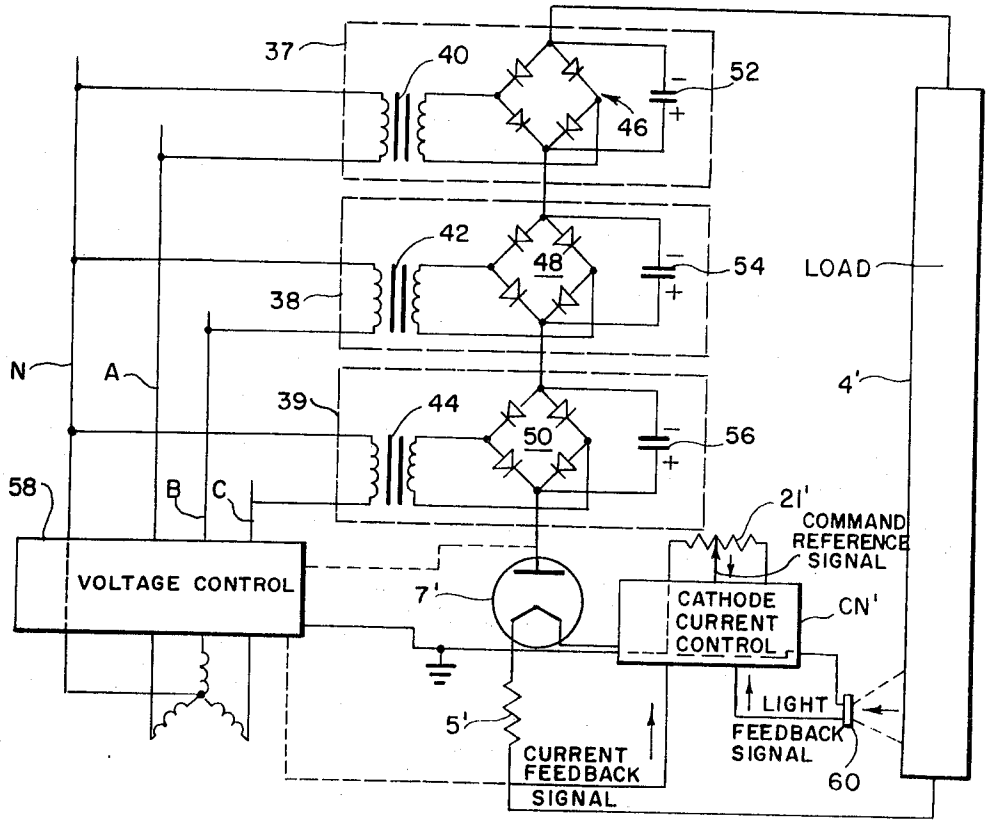

FIG. 6

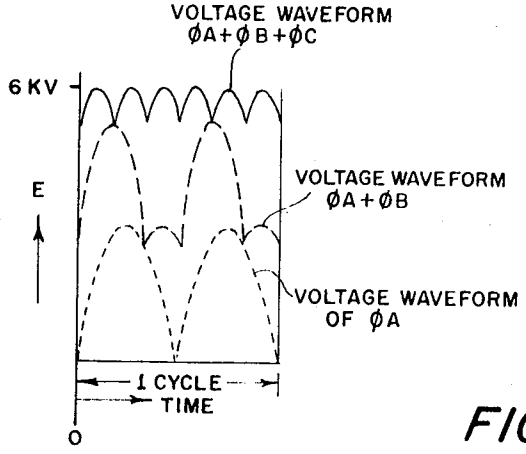

FIG. 6A

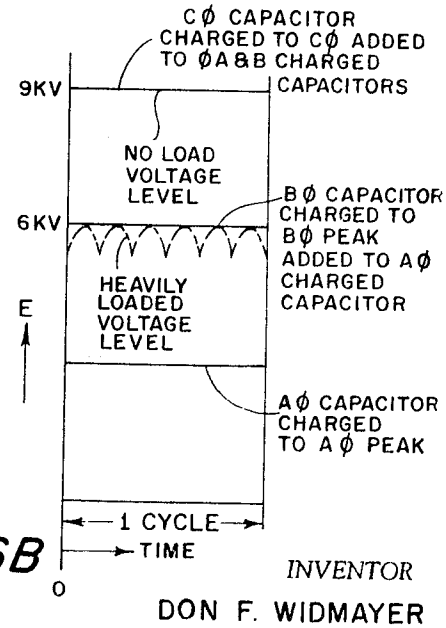

FIG. 6B

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ELECTRIC CURRENT CONTROL APPARATUS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the control of electric current and, more particularly and advantageously, to the control of a continuous current through a non-linear load device having either and/or both positive and negative regions on its volt ampere characteristic and high impedance loads.

2. The Prior Art

Most load devices are powered by a voltage source, e.g., an AC power line, which provides, except for line fluctuations, transients and loading variations, a "fixed" voltage. The current level in such devices complies with the voltage in correspondence to the ratio of the "fixed" source to the load resistance in accordance with the formula, $I=E/R$.

The classic method for controlling the current flow through a load device is to control the amplitude of the applied voltage. This method causes the current to comply to a level in accordance with a changed E/R ratio. In another approach the power to the load may be rapidly switched on-off-on-off by applying voltage or no voltage for various time increments, the higher the on-to-off ratio, the greater the average power flow to the load. This latter method of control is carried out at a sufficiently high frequency so that the load responds to the average current value. This latter method is extensively used in solid state circuits employing thyristors and in certain vacuum tube circuits.

While the hereinbefore described methods of voltage control are useful, they have unique as well as common disadvantages. For example, the current and, hence, the load device output will vary with occasional fluctuations in the voltage source which may occur between low and peak power consumption periods. Furthermore, the use of resistive elements to limit and to adjust the current is inefficient and often consumes as much or more power than the primary load device. The use of on-off switching for an average current value method of control is the most efficient of the methods discussed, but, among other shortcomings, does not necessarily compensate for primary voltage source variations.

The disadvantages of these methods of control become even more obvious and their utility even more limited upon consideration of their applicability to non-linear load devices in general and to the family of devices which depend upon gaseous discharge phenomena in particular, these latter devices including neon, fluorescent, mercury and other types of arc lamps, furnaces, welders as well as other gaseous arc devices. Such devices generally exhibit a volt-ampere characteristic which is negative in character over some portion of the current range. Because of this negative resistance characteristic the classic control methods described above are limited to controlling the arc current over relatively narrow ranges, if they are useable at all.

One form of such a load device which is particularly difficult to control is the fluorescent lamp. This type of lamp is representative of devices utilizing gaseous discharge phenomena to transform electrical power to light or other forms of radiant energy. The particular problem to be solved with fluorescent lamps is to provide stable arc operation and to vary or maintain the intensity of the radiation therefrom. The fluorescent lamp and other gaseous discharge types present an almost infinite resistance between its electrodes until a sufficiently high voltage potential is applied to strike an arc. Then, as the electron flow enters the arc discharge region of conduction, the arc path takes on a negative volt ampere characteristic sometimes called "negative resistance." Hence, if a voltage sufficient to strike the arc were applied to a fluorescent lamp, as might be applied to light a filament lamp, the current through the arc would attempt to go to infinity, thus producing a deleterious effect on the lamp or power source. To combat this tendency of the arc to attempt to go to an infinite current level a ballast is used, the primary function of which is to limit the current through the arc.

In AC operated gaseous discharge lamps the inductive reactance of a "choke" is conventionally employed as a ballast. Other circuitry and components are also employed to provide the higher starting than sustaining voltage required and the cathode heater voltage when independently heated cathodes are used. In AC operated gaseous arc discharge lamps the arc goes discontinuous at twice the AC power frequency. Therefore, on 60 cycle power operation the lamp develops a 120 CPS light fluctuation sometimes called "light ripple." Generally, the light fluctuation is not perceptible to the eye but on occasion appears to cause some noticeable flickering or spiraling effect which is also related to operation at lower temperatures or in drafts. Further, the conventional ballast requires a reasonably optimum line voltage. A ballast designed to operate on a 117 VAC circuit will generally operate at up to 125 volts without causing overheating and at as low as 110 volts without causing flicker or starting difficulties or reduced lamp life due to the reduced cathode voltages and other factors. In addition, the 120 CPS fluctuation, while not visible to the eye, causes a stroboscopic phenomenon observable on rapidly moving or rotating objects. Further, the phenomenon of the arc going discontinuous and restriking at twice the power frequency generates RF transients requiring RF interference suppressors.

In DC operated gaseous arc discharge lamps a resistor is conventionally used to limit the current along with a choke type ballast to supply an inductive voltage "kick" for starting the lamp. The main disadvantage of DC operation is that in the case of a fixed arc level the resistance-ballast consumes roughly the same power as the lamp and increases greatly if wide range arc current control is required, thus making conventional DC operation considerably less efficient than conventional AC operation. However, the problems of RF interference, strobe effects, fluctuation, flicker and spiraling effects due to the line voltage fluctuation are not present in DC operation.

The gaseous arc lamp requires an arc sustaining voltage and the rapid change from an almost infinite resistance in the "off" state to a negative resistance characteristic in the "on" state precludes a wide range of control by simple voltage variation. Lowering the voltage will first nominally dim the lamp, then cause flicker and then extinguishment. To maintain maximum sustaining voltage "on" time, conventional AC ballasts attempt to transform the AC sine wave input power into an AC square wave character because without such a transformation the "on" time provided would be even shorter in that this time would be otherwise confined to the time period in which the AC wave peak exceeds the arc sustaining voltage level required.

Another more widely used technique for controlling the lumen output of gaseous arc discharge lamps, which is also used to control incandescent type lamps as well, is one in which a silicon control rectifier and accompanying circuitry drive the lamp "on" over only a portion of the primary AC power source wave form. This mode of operation will extend, but still to a limited extent, the dimming range of gaseous arc lamps. In the case of a gaseous arc lamp controlled by a SCR control circuit, the total lamp power is generally controlled and perceptible flicker begins to become apparent when the SCR "off" time beings to exceed the SCR "on" time. In all voltage control systems the radiant energy output will follow line voltage variations and changing lamp characteristics such as temperature effects on its vapor pressure. A further problem in conventional controlled gaseous discharge type lamps is that the lumen output decreases, rapidly at first, with operating lamp life.

SUMMARY OF THE INVENTION

In accordance with the present invention means are provided for controlling, over a wide dynamic range, a continuous current through a load independently of the resistance characteristics of the load and, in a specific application, for con-

trolling the arc current through a load device dependent upon gaseous discharge phenomena over a widely adjustable operating range utilizing a continuous arc current.

In accordance with the invention an arrangement is provided wherein a control means is connected in series with the load and operated in mode wherein the current through the control means is independent of the voltage thereacross so that the current supplied to load is not a function of the volt-ampere characteristics of the load. In one presently preferred embodiment of the invention, the control means provided is a vacuum tube diode connected in series with the load. The voltage across the tube is maintained at a value sufficient to keep the cathode operating in an emission limited mode wherein the current conduction of the tube is principally a function of the thermionic emission characteristics of the tube cathode and is substantially independent of the voltage on the tube. Thus by controlling a heating current level through the cathode the current conduction of the tube can be controlled independently of the resistance characteristics of the load. This approach furnishes a reliable and efficient approach to current control.

In accordance with a further feature of the present invention a novel multiphase power supply useable but not limited to use for certain lamp loads is provided which comprises a number of rectifier bridges individually connected to the phases of a multiphase system. The outputs of the bridges are connected in series with the load and with each other such that the outputs are summed. This method of rectification provides certain important advantages which are described hereinbelow over conventional multiphase rectifying arrangements.

In accordance with yet another feature of the present invention the voltage supplied to the tube-lamp circuit is varied to meet the requirements of the lamps with change in current therethrough but is maintained at a level sufficient to keep the tube operating in its emission limited mode whereby the plate dissipation of the tube is controlled and circuit losses are minimized.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the present invention will be apparent upon reference to the accompanying specification when taken in conjunction with the drawing wherein:

FIG. 1 is a static representation of the volt-ampere characteristic of a typical gas discharge device. Under dynamic operating conditions this character will vary considerably from the illustration as a function of temperature:

FIG. 2 is a schematic diagram of a circuit in accordance with the invention for controlling electrical current to a "grid" type fluorescent lamp of the gaseous discharge type;

FIG. 3 is a diagram representing the volt-ampere plate characteristics of the high vacuum tube of FIG. 2;

FIG. 4 is a diagram representing the electron emission in terms of plate current versus cathode heating current of the high vacuum tube of FIG. 2;

FIG. 5 is an approximate representation of the source voltage distribution across the various system components as a function of load current;

FIG. 6 is a schematic diagram of a three phase higher power system incorporating the invention; and

FIGS. 6A and 6B are wave forms used in explaining the operation of the circuit of FIG. 6.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, the volt-ampere characteristic C of a typical gas discharge type is represented. The blank area preceeding the point denoted 1 on curve C would normally include the Townsend, transition, normal glow and the beginning of the anomalous discharge regions. The actual portion of volt-ampere curve C illustrated is intended to represent the remainder of anomalous glow and arc discharge region. Because of the exceeding complexity and marked non-linearity of the portion of the volt-ampere curve in the area preceeding point 1 illustration of this portion of the curve has been omitted for purposes of clarity. It can be seen that the curve beginning at point 1 is a positive volt-ampere curve up to the knee identified by a point on curve C denoted 2 at which point the curve turns negative as may be seen by a comparison of point 2 with a point denoted 3 higher up on curve C. It is noted that the voltage amplitude throughout the curve C may further vary from that shown as a function of lamp vapor pressure which varies due to internal heating.

Referring now to FIG. 2 of the drawing, the present invention is shown incorporated in a circuit for controlling the current through a long arc gridded type fluorescent lamp 4 which is connected in series relationship with a pair of resistors 5 and 6, a high vacuum tube diode 7, a resistor 8, and a full-wave bridge 9. An AC voltage source is stepped up to 2175 VAC by a transformer 10, whose secondary is connected to the full-wave rectifier bridge 9. The rectified 2175 AC source voltage provides a nominal 3,000 VDC source to the series circuit of lamp load 4 and control element 7. The positive and negative terminals of bridge 9 are connected to a filter capacitor 12 and a resistor 11 connected in parallel with capacitor 12 serves as a discharge path for the stored energy in capacitor 12 when the system is de-energized. Vacuum tube 7 is a vacuum tube diode with a tungsten or thoriated tungsten cathode which may for example be a GL **8020** tube. An important characteristic of this and similar type tubes such as the 3B 24W or the GL 5973 tubes is that such tubes have exceedingly high voltage withstand ratings. Further, these tubes can stand large high currents and/or high plate dissipations for short time periods.

All of these tubes have tungsten or thoriated tungsten filamentary cathodes which can be operated in a temperature limited emission mode. Therefore, the plate current, provided that sufficient plate voltage is available to ensure current saturation, is primarily a function of cathode temperature. A typical current saturating voltage is represented by reference numeral **30** in FIG. 3. The following basic ratings apply to these three tubes:

Tube type	3B 24W	GL 8020	GL 5973
Maximum steady state DC current	60 ma	100 ma	1,250 ma
Maximum steady state plate dissipation	25 watts	75 watts	850 watts
Peak inverse voltages	20 KV	40 KV	40 KV

It is noted that parallel combinations of a particular tube with suitable current sharing circuitry may be employed to obtain different current levels.

Another important characteristic of a high vacuum diode tube is that the electronic emission of the cathode is highly non-linear. The electron emission versus cathode heating curve of FIG. 4 illustrates that no useful electron emission takes place, in the specific instance of a GL 8020 tube, with less than 2.5 amperes average cathode heating current. Therefore, a high voltage source can be connected to the series "-tube-load" circuit shown in FIG. 2 but no load current will flow until the cathode heating current is of a value in excess of 2.5 amperes average DC. The series load current is represented in FIG. 2 by a dotted line denoted 13. When a load current is flowing, voltages will exist across load 4 and resistors 5, 6 and 8 corresponding to load current 13, while the remaining source voltage will appear across tube 7. In these circumstances the actual series load current 13 is a function of the thermionic emission of the cathode which is controlled by a cathode heating current feedback control circuit including a cathode current control network generally denoted CN described hereinbelow.

A transformer 16 provides a 6.3 AC secondary winding voltage to a full-wave bridge 17 whose negative terminal is connected to the common bus and whose positive terminal is connected to the common bus through the cathode of tube 7 and a two-ohm resistor 6. Therefore a nominal two ampere

current represented by the long dashed lines denoted **15** will flow in the cathode circuit. This current level is below the cathode-to-anode current electron emission threshold of a GL 8020 tube as discussed hereinabove and thus no useful electron emission will take place. Current **15** reduces the thermal lag when an additional controlled current described below is included and also reduces the power dissipation burden on the active control current device used in producing this controlled current, namely, a transistor **18**.

The controlled current which is represented by the short dashed lines denoted **14** in the cathode heating circuit is achieved by feedback control of the transistor **18** which is connected in shunt across resistor **6**. Because current leakage through transistor **18** is of no concern in that the nominal value of current **15** is well below that required for electron emission, an economical germanium type transistor may be employed. Such a transistor will, fortuitously, exhibit higher gain in the higher current regions than an equivalent and more expensive silicon type transistor. A small signal silicon transistor **19** is employed to drive transistor **18** to produce a higher level of forward gain and thus reduce the required value of a controlling error signal described below to a very low level.

A command input reference signal is derived from a resistor network formed by a resistor **20** and potentiometer **21**. One terminal of potentiometer **21** is connected to the base of transistor **19** while resistor **20** is connected in series with the potentiometer tap **21a** as shown in FIG. **2**. A feedback signal is derived from a resistor network formed by a resistor **22** and the resistor **5**, resistor **22** being connected between a point on the connection between potentiometer **21** and transistor **19** and a point on the connection between resistor **5** and load **4**. A capacitor C connected across resistor **5** acts as a filter for the feedback control signal resistor network. The command input reference signal power supply includes a full-wave bridge formed by a pair of diodes D1 and D2 and a pair of diodes D3 and D4 shared with full-wave bridge **17**. The input of the bridge so formed is connected in circuit relation to transformer **16** while the output is connected in circuit relation with a capacitor **26**, a current-limiting resistor **27**, a zener diode **28** and a silicon diode **29**. Capacitor **26** is connected across the output terminals of the bridge in parallel with the series leg including diodes **28** and **29**. The other terminal of potentiometer **21** is connected to a point on the connection between the two diodes **28, 29** while resistor **27** is connected between the positive output terminal of the bridge and the zener diode **28**. The 6 ampere rated 6.3 AC secondary voltage of transformer **16** is rectified by the bridge formed by diodes D1 to D4 so that capacitor **26** is permitted to charge up to the peak voltage of transformer **16** which is nominally 9 volts at no load. Current limiting resistor **27** provides a current path from the plus 9 volt level through zener diode **28**, rated at 6.4 volts, and silicon diode **29** to the common bus. Hence, diode **29** provides a reference voltage point nominally 700 millivolts above the common bus and thus provides first order matching with the 700 millivolt offset of the base of transistor **19** due to its base to emitter diode drop. The tap or wiper arm **21*a*** of potentiometer **29** is connected through resistor **20** to the anode of zener diode **28** which provides a regulated 6.4 voltage reference above the anode of diode **29**. With this arrangement the current flowing through resistor **20** can be proportionally steered to diode **29** or into the base of transistor **19** as a function of the setting of potentiometer wiper arm **21*a***. The current flowing from the potentiometer **21** to the summing node is the input command reference signal and is of positive sign so that this current causes transistors **19** and **18** to conduct. With transistors **19, 18** conducting the cathode current will increase beyond the two ampere limit determined by the value of resistor **6** and consequently the cathode emission of tube **7** begins and load current **13** is permitted to flow in the series load circuit. A voltage across resistor **5** will be developed corresponding to the value of load current **13** and a negative sign current signal flowing from resistor **22** will be fed back to the summing node. The positive sign input reference signal and the negative sign current feedback signal are algebraically summed on the base of transistor **19**. The sum of these two signals is the error signal which controls the electron emission of the cathode. With tube **7** in a current saturated state caused by a sufficiently high voltage across the anode and cathode the electron emission of the tube will determine the current through the load **4**. Thus, by controlling the setting of potentiometer **21** the current through diode **7** and thus through lamp load **4** may be controlled. It will be appreciated that tube **7** provides current limiting for the system in that once the saturating voltage thereof is exceeded the current therethrough is a function of the emission characteristics of the tube and is independent of the load resistance.

Resistor **8** serves as a voltage dropping resistor to relieve tube **7** from excessive plate dissipation at higher plate current levels. Resistor **8** must be selected so that sufficient voltage remains across the tube **7** at all operating current levels so that the tube remains in a current saturated mode with some excess voltage to provide both an upward and downward current regulating range. Voltages **31, 32** and **33** of FIG. **5** are approximations of the voltages appearing, respectively, across the lamp load **4**, the tube **7**, and the resistor **8** in FIG. **2** as a function of the load current **13**. The dashed and solid curves **34, 35** corresponding to the voltage drop across lamp load **4** indicate variations in the lamp that may be encountered due to changes in the ambient temperature levels of operation and to vapor pressure changes due to internal heating.

The system heretofore described has been applied to a film viewing table wherein a relatively low current grid high voltage type of fluorescent lamp was employed. The invention described however is equally applicable, with suitable component changes, to driving higher current lamps up to and including the 1,500 milliampere T–**12** fluorescent lamps connected in series as well as to driving resistive loads. Further, the cathode control circuit could incorporate a lumen feedback or temperature sensor to adjust the cathode current as a function of "light" output, lamp temperature or combinations of these and other variables.

For some higher power applications the single-phase primary power source shown in FIG. **2** could be inadequate from an electrical service standpoint as well as from a consideration of the size and rating requirements of the energy storage component **12**. A typical example of a high power negative volt-ampere characteristic load is a series connected array of fluorescent or other type of discharge lamps which are often employed in plant growth research chambers. Such an array might typically consist of 32 eight-foot fluorescent lamps operating at currents ranging from less than 10 milliamperes to one or more amperes. Depending on the type of fluorescent lamp and the current drive level the voltage across each lamp can range from 150 volts at higher current levels to as much as 300 volts at low currents. Therefore, from the standpoint of electrical service and from a consideration of the storage component rating requirements, a polyphase electrical source is generally desirable in a multi-kilowatt system.

In FIG. **6** a high power system is shown which operates in a similar manner to the system shown in FIG. **2**. The system of FIG. **6** differs from that of FIG. **2**, in general, in the nature of the power supply provided and similar elements have been given the same numbers with primes attached. The load **4'** may comprise an array of lamps as described hereinabove. In accordance with a further feature of the invention a novel three-phase power supply is provided which includes three transformer-rectifier sections denoted **37, 38** and **39**. Sections **37** to **39** include three single-phase transformer assemblies generally denoted **40, 42** and **44**. One side of a primary winding of each transformer is connected to the neutral conductor N of a three-phase four-wire "wye" source of voltage while the other sides of the primary windings of each of the transformers **40, 42** and **44** are respectively connected to phase conductors A, B and C. It is noted that the primary connections could of course be equally well adapted to a three-phase delta

voltage source in lieu of the "wye" source described. The individual secondary output voltages of the transformers **40, 42** and **44** are rectified by corresponding associated full-wave diode bridges **46, 48** and **50**. Because the secondary voltages are isolated by the transformers from the primary voltage source respective positive and negative terminals of the three bridges **46, 48** and **50** can be connected in series as shown and thus the three distinct phase voltages are summed.

FIG. **6A** illustrates the voltage waveform of phase A, the summed voltage waveforms of phase A plus phase B and the summed voltage waveforms of phases A, B and C. It will be noted that the voltage wave shape of the three summed phases is the same as that which would be produced by a conventional six element three-phase rectifier bridge and transformer arrangement. However, the rectifying arrangement of the invention wherein the three phases are individually rectified and then summed provides certain advantages which may not be immediately obvious. By way of example suppose that the voltage peak shown in FIG. **6A** is 6,000 volts. For such a voltage each of the six rectifying elements of a conventional three-phase rectification arrangement would have to have a voltage withstand rating of 6,000 volts plus whatever over-rating is required for line changes and transients. In the arrangement of the invention, while twelve rectifying elements (three sets of four elements for each phase) are required, the voltage withstand rating of each rectifier need only be one-half of the peak 6,000 volts plus the required over-rating for a safety margin. From an economic standpoint it is noted that the high voltage rectifier elements are generally much more expensive than the lower voltage rectifier elements due generally to the much larger market for the lower voltage elements and that this fact offsets the cost of using twice as many rectifier elements in the arrangement of the invention. Further, it is noted that under circumstances where the upper voltage limit of the rectifier elements is reached the voltage summing method of the present invention allows for a much higher rectified voltage supply.

Referring again to the three power supply sections **37–39** of FIG. **6** individual capacitors **52, 54** and **56** are connected across the respective positive and negative terminals of the full wave bridges **46, 48** and **50**. With these capacitors **52, 54** and **56** added to the supply sections the wave forms shown in FIG. **6A** are altered depending on loading. FIG. **6B** illustrates the two load extremes, namely, no load and a load current sufficiently high that the energy of the capacitors, and therefore the effects thereof, are negligible. It will be noted that under no load conditions FIG. **6B** shows a ripple free DC level 50% higher than the peak voltage shown in FIG. **6A**. Depending upon the load current and the ratings of the three capacitors **52, 54** and **56** the voltage level in FIG. **6B** can decline down with increasing ripple until the shape thereof reaches the wave shape indicated in dashed lines corresponding to 6,000 volts. In contrast, it is noted that for capacitive filtering of the abovementioned conventional three phase power rectifier arrangement the new load voltage would never exceed the 6,000 volt peak and would manifest itself only by an increase in ripple with loading down to the peak-to-valley wave shape illustrated in FIG. **6A**.

With proper sizing of the capacitors the capacitive effect discussed above can be useful particularly in the case of gaseous discharge type of loads such as employed in the system of FIG. **6** wherein the striking of an arc in the lamps requires a high voltage potential across the load for ionization purposes before the arc is struck. A further advantage of this capacitive effect is that where a motorized auto-transformer pre-regulating voltage control is employed to operate the control element vacuum tube within the plate voltage and dissipation limits thereof as discussed above, the system need not wait for the relatively slow pre-regulator to increase the applied transformer voltage. In such a system small value capacitors can be employed so that the voltage substantially declines immediately upon the striking of the arc. Alternatively, high value capacitors can be employed so that the voltage substantially declines immediately upon the striking of the arc. Alternatively, high value capacitors could be employed in a manner such that the voltage declines as the load current increases, which effect, for negative volt-ampere characteristic load applications, would obviate the need for or at least minimize the amount of voltage pre-regulation required to maintain the anode-to-cathode voltage level within the required limits.

A further advantage of the voltage summation method of the invention is that although the three phases of FIG. **6** are shown in series relationship above the plate of tube **7'** in actual practice one or two of the phase voltages may be and generally would be connected below ground, between, for example, the current feedback sense resistor **5'** and the load **4'**. With this arrangement the voltage to ground would be lowered by splitting the total voltage into portions above and below ground while maintaining the control circuitry at about ground.

Another important advantage of using the three-phase power system of the invention is that no matter how the system is configured the rectified voltage will never go to zero and the energy storage component requirements for a given power level are considerably less than those for a single-phase system wherein the voltage goes to zero two times during each cycle.

Referring again to the circuit of FIG. **6** it is noted that a GL **5973** vacuum tube diode may be employed as the control element **7'**. The cathode heating current control circuit CN' may be similar to the cathode heating circuit CN shown in FIG. **2** but would operate at a higher level. The circuit of FIG. **6** includes a current feedback signal as described above as well as a light feedback signal loop. The light feedback signal loop may include a light sensitive device **60** such as a photocell which produces an electrical output which is a function of the radiation intensity of the lights. In practice, either or both loops may be used. Specifically, if the load current is taken as the controlled variable the current feedback loop would be employed. On the other hand, if the radiation output of the lamp load is to be taken as the controlled variable the light feedback loop would be employed. Alternatively, the current loop could be an inner loop and the light feedback loop an outer loop for increased stability and accuracy.

It is noted that in higher power systems dissipative elements such as resistor **8** in FIG. **2** would be undesirable and thus some form of active voltage control would appear to be desirable to prevent over-rating dissipation at the anode of the vacuum tube **7'**. In this regard FIG. **6** shows a voltage control pre-regulator **58** which senses the voltage between the cathode and anode of tube **7'** as well as the load current and which causes a decrease in the voltage applied to the transformer primaries of transformers **40, 42** and **44** when the plate dissipation of tube **7'** becomes excessive. Alternatively the preregulator **58** acts to increase the voltage applied to the transformer primaries under circumstances where there is insufficient cathode-to-anode voltage to maintain current saturation of the tube **7'**. It is noted that a thermal sensing couple to the anode of tube **7'** may be substituted for the voltage sensing conductive couple described hereinbefore in that the plate dissipation limits for such tubes are primarily a function of the plate temperature requirements necessary to protect the tube seal and thus insure that a vacuum is maintained. With the temperature sensing arrangement it would not be necessary for the load current to be sensed by the voltage control regulator.

In accordance with a further embodiment of the invention a power triode, pentode or like tube could be substituted in lieu of the emission limited diode tube shown in FIGS. **2** and **6**. With such an arrangement the load current would be controlled by a signal to the grid current of the tube. However, because the plate withstand voltages of power triodes and pentodes are substantially lower than those of the filimentary high vacuum diode tubes described hereinabove, the voltage preregulation becomes more critical. This statement is particularly true with regard to the negative volt-ampere type of

load wherein the voltage across the load may decline very rapidly with an increase in current thus meaning that the voltage across the control tube will increase with corresponding rapidity until whatever voltage control unit is employed acts to lower the voltage applied to the transformer input.

Among the various types of voltage control systems three types of voltage control appear to have particular value for the applications discussed above; (1) simple tap relay switching for fairly gross control, (2) a motorized autotransformer for fairly fine but still relatively slow control and (3) SCR or Triac phase angle control for relatively fast control response. All three types are useful for systems employing the filimentary type vacuum diode but the use of a space charge type of tube such as a power triode would probably require the faster acting SCR voltage regulating system. For the case of a voltage regulating system utilizing SCR or Triac control a smoothing choke would have to be employed in the series load circuit as an energy storage component to integrate the volt-second pulses of power.

For positive volt-ampere characteristic loads a system using the filimentary type vacuum diode may not require an active voltage regulator because some degree of voltage regulation relative to load current can be achieved with passive elements and because a diode tube can withstand such high cathode-to-anode voltage as might be present at low load currents. However, the cathode-to-anode voltage withstand ratings of grid control space charge tubes would normally preclude their use in a high voltage system without the inclusion of a relatively fast acting voltage preregulator.

The mercury ion migration problems encountered in fluorescent lamps when operated with a DC source become more severe at higher current drive levels and accordingly, a means for providing a periodic polarity reversal is generally required. For the system of FIG. 6 suitable switching logic circuit for reversing the polarity each time the system is energized might be acceptable. Alternatively, a double-pole double-throw vacuum relay and timing device to periodically switch polarity while the lamps are operating might be a preferred method for many applications.

Although the invention has been described in some detail with reference to presently preferred embodiments thereof it will be understood that modifications other than those specifically enumerated may be effected without departing from the scope and spirit of the invention. Thus the scope of the invention is to be determined not from the illustrative embodiment described hereinbefore but rather from the subjoined claims.

Having described my invention in accordance with the requirements of the Patent Statutes, I claim:

1. A current control system comprising a load, means for supplying current to said load, and current control means, comprising a vacuum tube operated in a temperature limited emission mode wherein the current through the tube is independent of the voltage thereacross, connected in series with said load for controlling the current through the load irrespective of the volt-ampere characteristics of the load.

2. A current control system in accordance with claim 1 wherein said means for supplying current to said load comprises a polyphase source of voltage and a number of rectifier bridges individually connected across respective of the phases of said polyphase voltage source, the number of rectifier bridges being equal to the number of phases and the outputs of said rectifier bridges being connected in series with each other and with said load whereby the outputs of the individual rectifying bridges are summed.

3. A current control system in accordance with claim 1 wherein said current supply means comprises feedback means for supplying current to said vacuum tube in accordance with a sensed quantity related to the output of said tube.

4. A current control system in accordance with claim 1 wherein said current control means further comprises means including a first diode rectifying bridge for supplying a continuous current to said tube and means including a second diode rectifying bridge for supplying a controlled current to said tube, said first and second bridges including diodes common to both bridges.

5. A current control system in accordance with claim 1 wherein said vacuum tube comprises a vacuum-type diode including a filamentary element.

6. A current control system in accordance with claim 5 wherein said current supply means comprises means for supplying a continuous current to said filamentary element and feedback means for supplying a controlled current to said filamentary element in accordance with a sensed quantity related to the output of said tube.

7. A current control system in accordance with claim 5 wherein said current supply means comprises said feedback means including a feedback resistor connected in series with said load for sensing the current through said tube.

8. A current control system in accordance with claim 7 wherein said current supply means includes an electronic means having conducting and non-conducting states and means for controlling the state of said electronic means, said control means including a source of regulated voltage, a further electronic means having conducting and non-conducting states for controlling the state of said first named electronic means, and a potentiometer connected between said source and said further means for variably controlling the state of said further means.

9. A current control system in accordance with claim 8 wherein said feedback resistor is connected in circuit relationship with said further electronic means for producing an error signal for controlling the state of said further electronic means.

10. A current control system in accordance with claim 7 wherein said current supply means further comprises a source of D.C. voltage and a germanium transistor connected in series with said D.C. source and said filamentary element.

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