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 [22] Filed **Mar. 17, 1969**
 [45] Patented **June 29, 1971**
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3,265,930 8/1966 Powell, Jr 315/209
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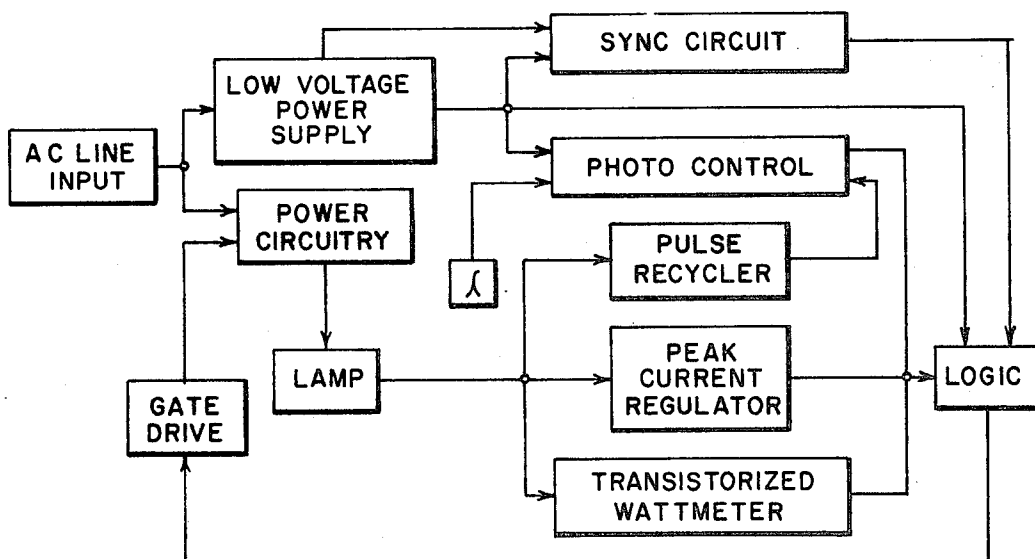
[54] **PHASE-CONTROLLED UNIVERSAL BALLAST
 FOR DISCHARGE DEVICES**
 10 Claims, 21 Drawing Figs.

[52] U.S. Cl. 315/209 R,
 315/308, 324/142
 [51] Int. Cl. H05b 37/02
 [50] Field of Search 315/209,
 225, 293, 299, 306, 307, 308; 324/142

[56] **References Cited**

UNITED STATES PATENTS
 3,226,641 12/1965 Miller 324/142

ABSTRACT: Apparatus for ballasting any of a plurality of discharge devices having varying voltage and current operating characteristics in order to operate a discharge device at about a predetermined wattage rating. A ballasting impedance limits the maximum current through the operating device and a semiconductor switch is closed in response to a triggering signal to vary the average wattage consumed by an operating device. The circuit includes a solid-state wattmeter having an input portion which develops a signal which is proportional to the current drawn by an operating device, as well as a signal which is proportional to the voltage drop across an operating device. These signals are combined to generate a signal which represents the logarithm of their product. The logarithmic signal is then converted into an antilogarithmic signal which in turn is averaged. The resulting averaged signal controls the triggering of the semiconductor switch to maintain the wattage input to an operating device at about its predetermined desired value.



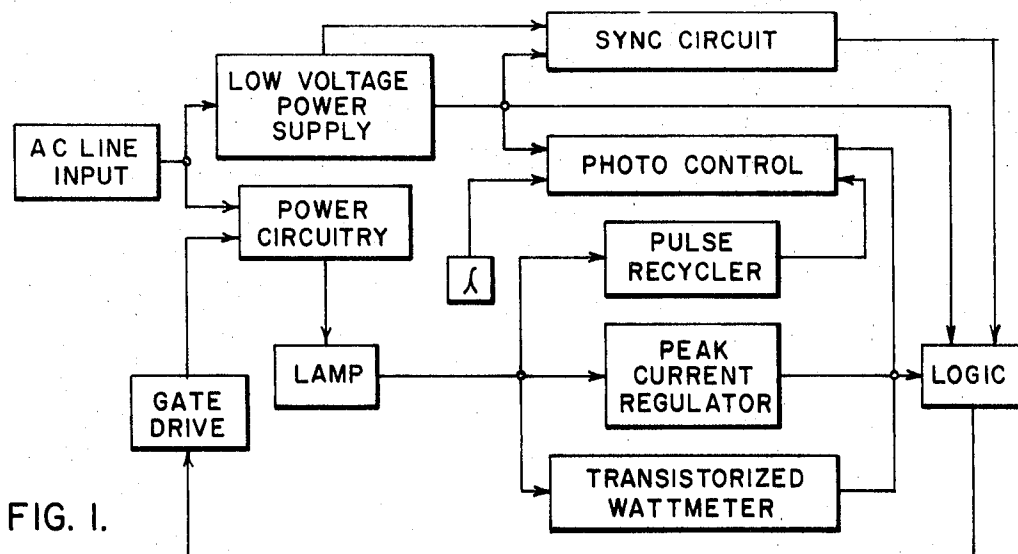


FIG. 1.

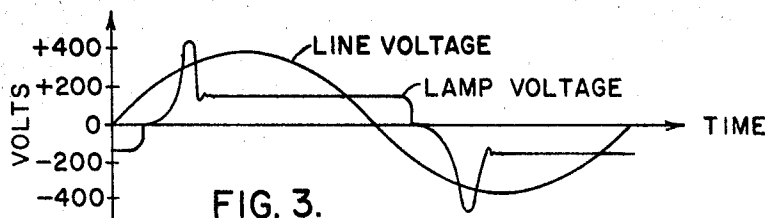


FIG. 3.

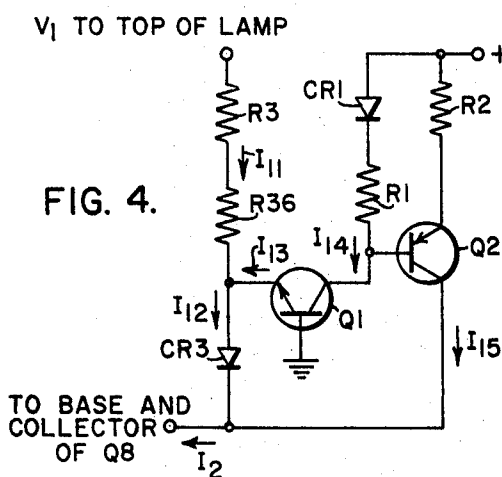


FIG. 4.

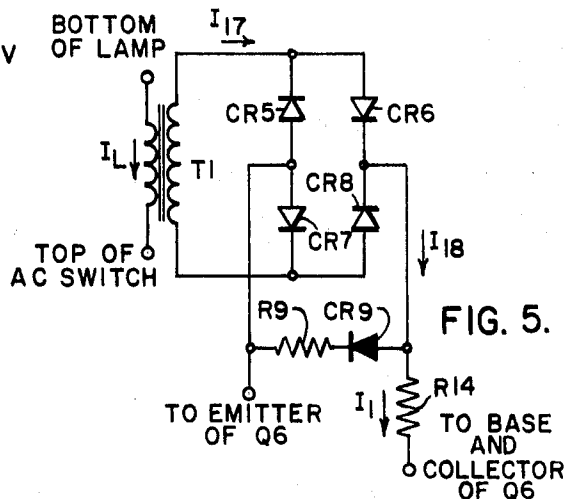


FIG. 5.

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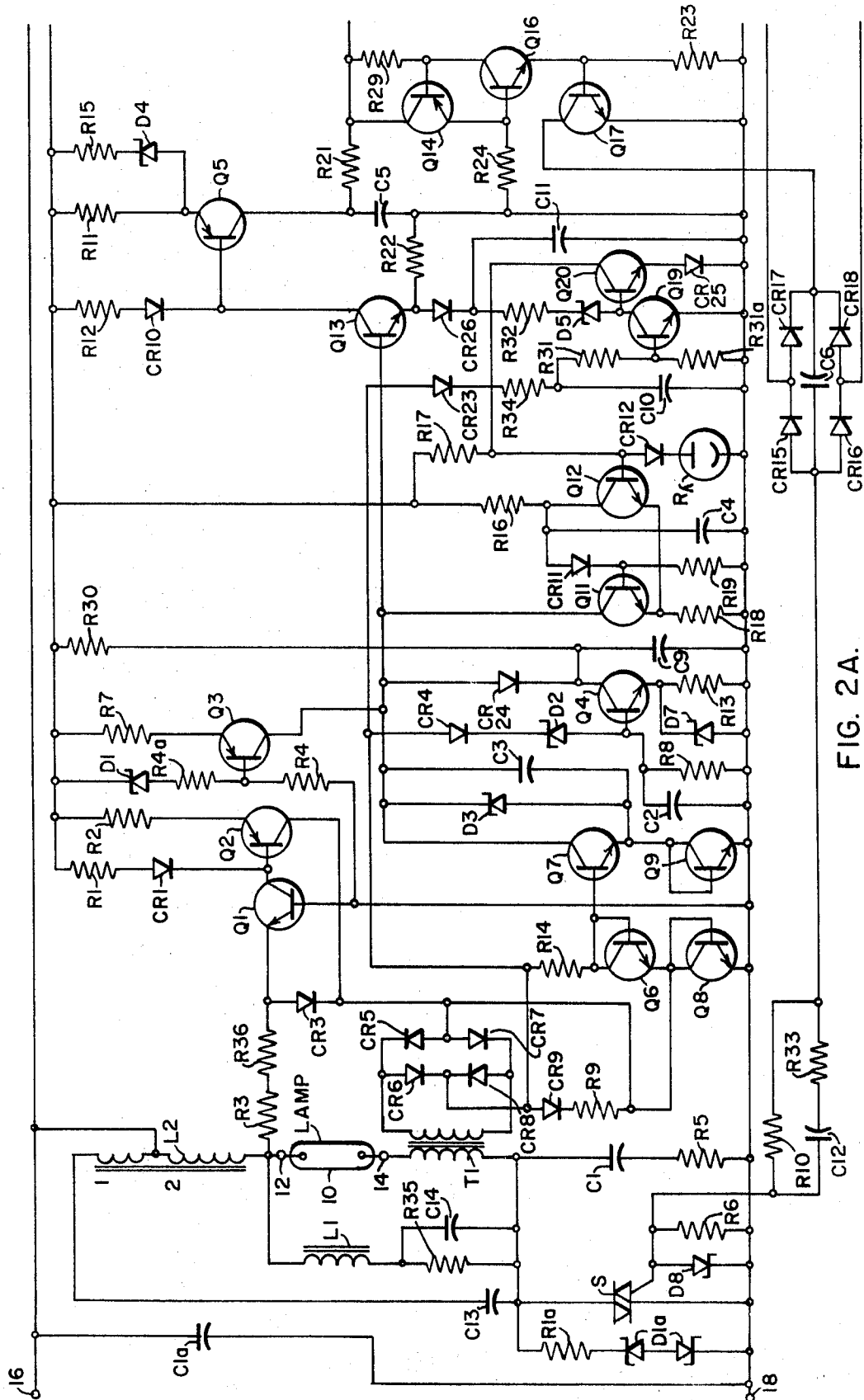


FIG. 2A.

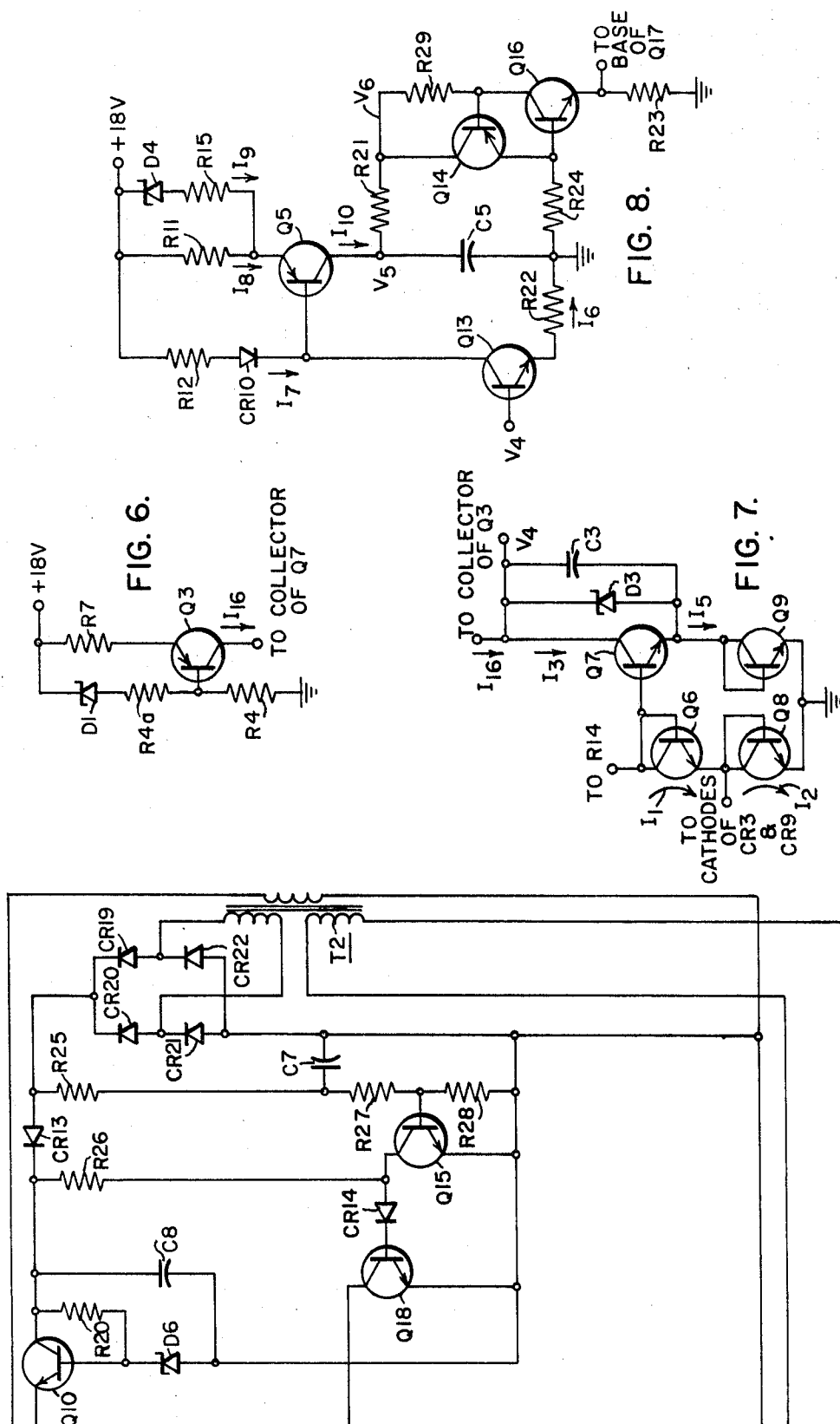
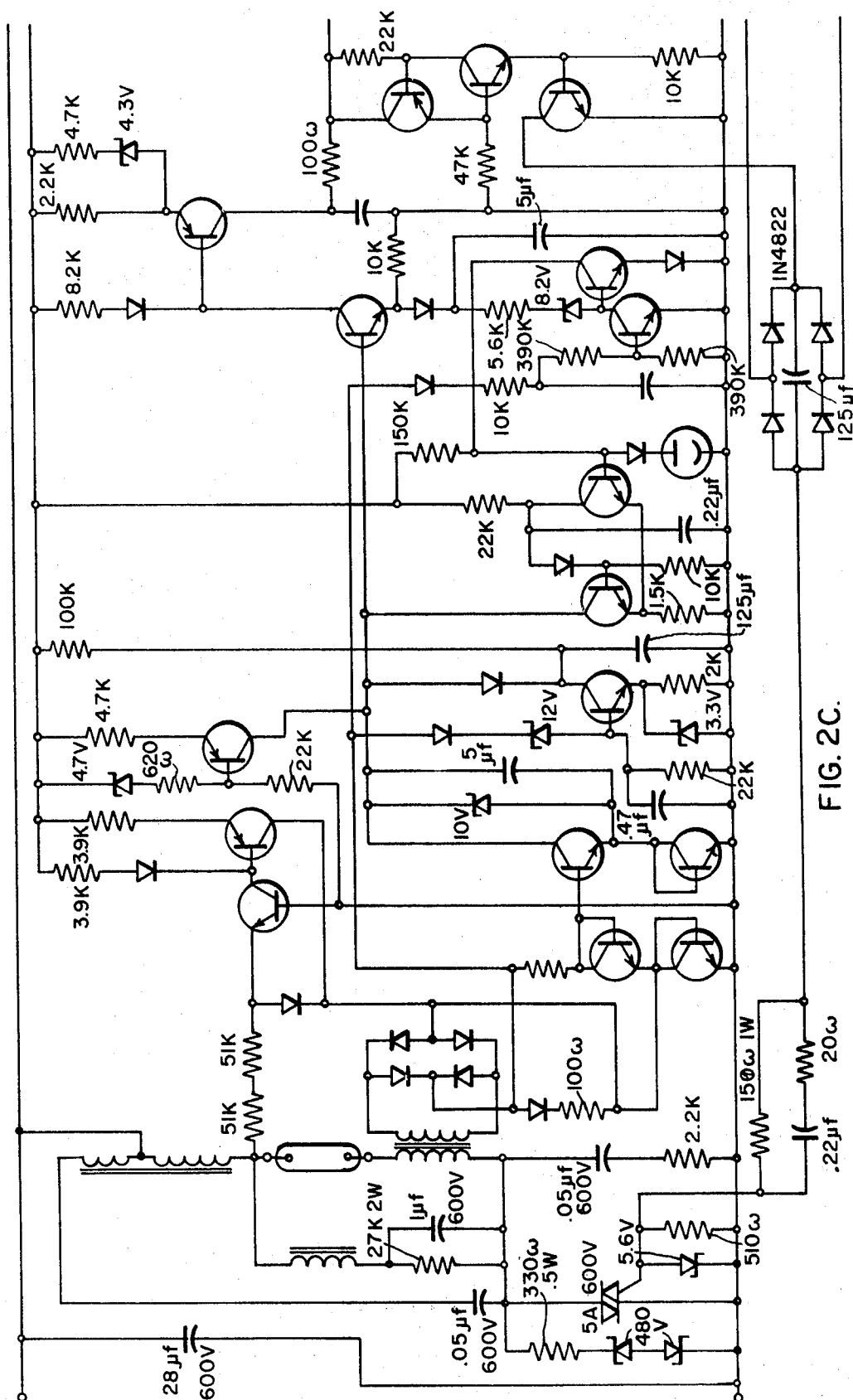
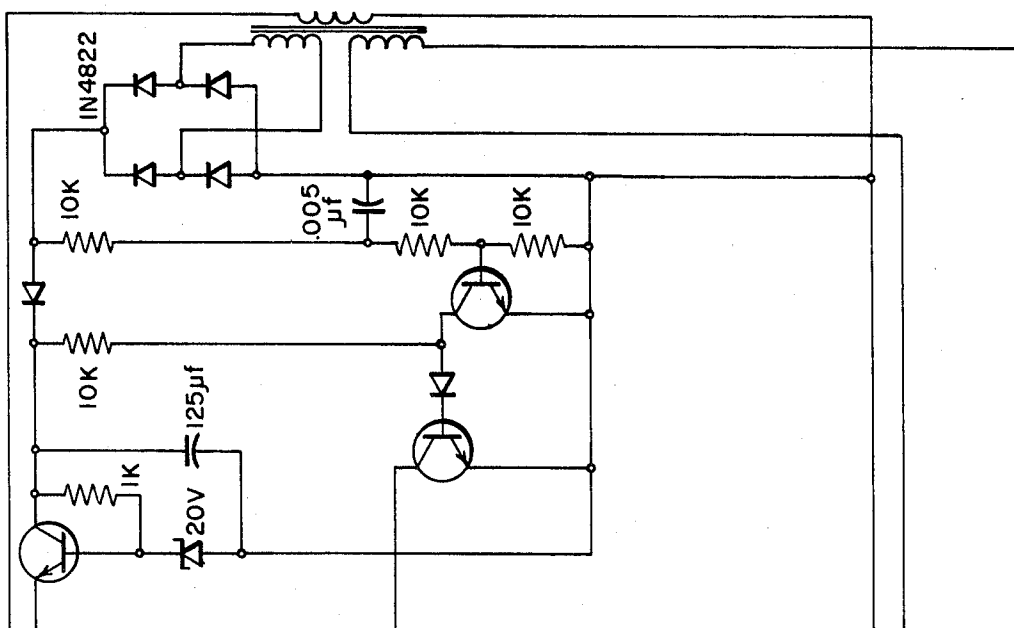
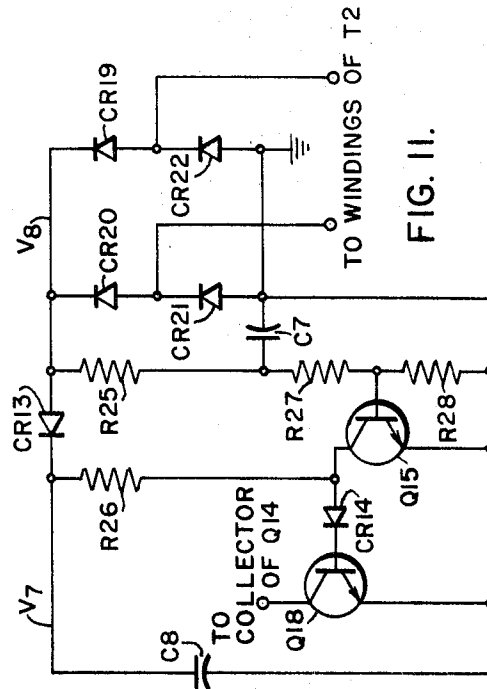
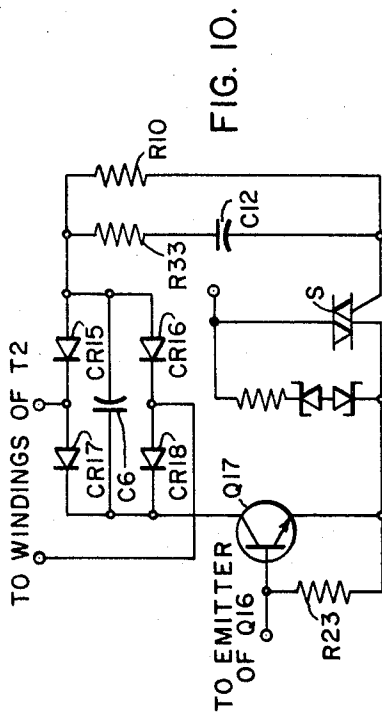
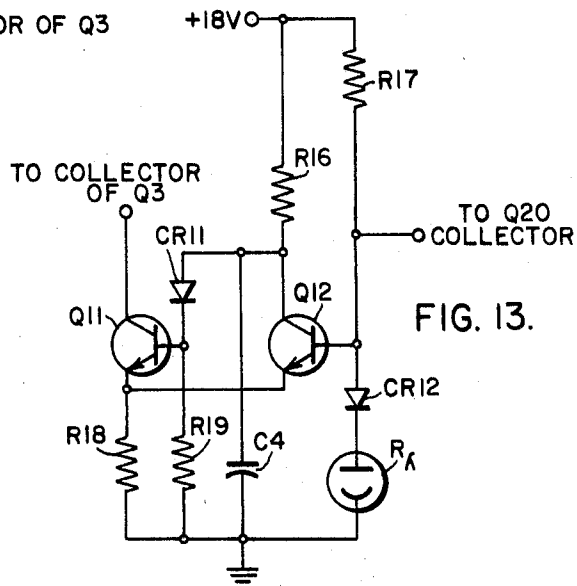
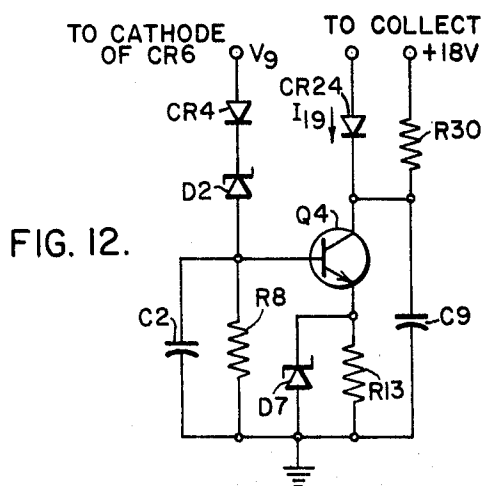
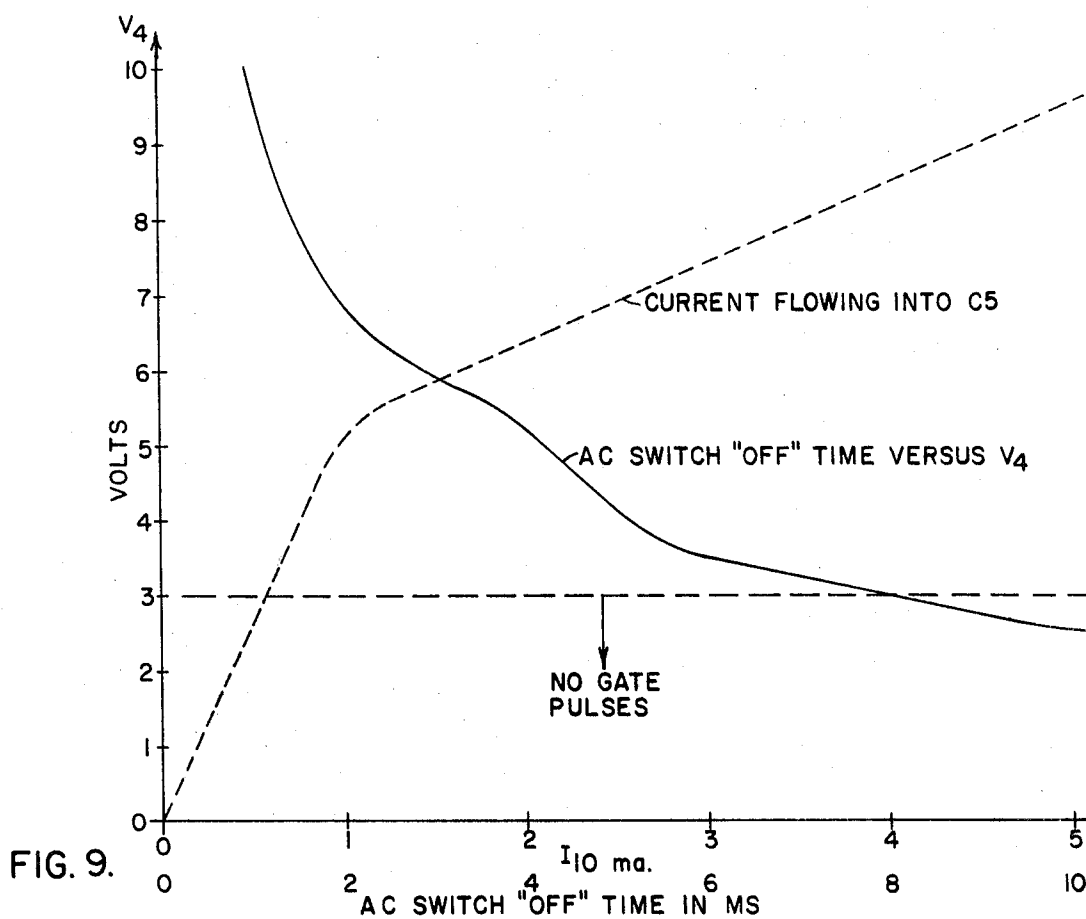


FIG. 2B.







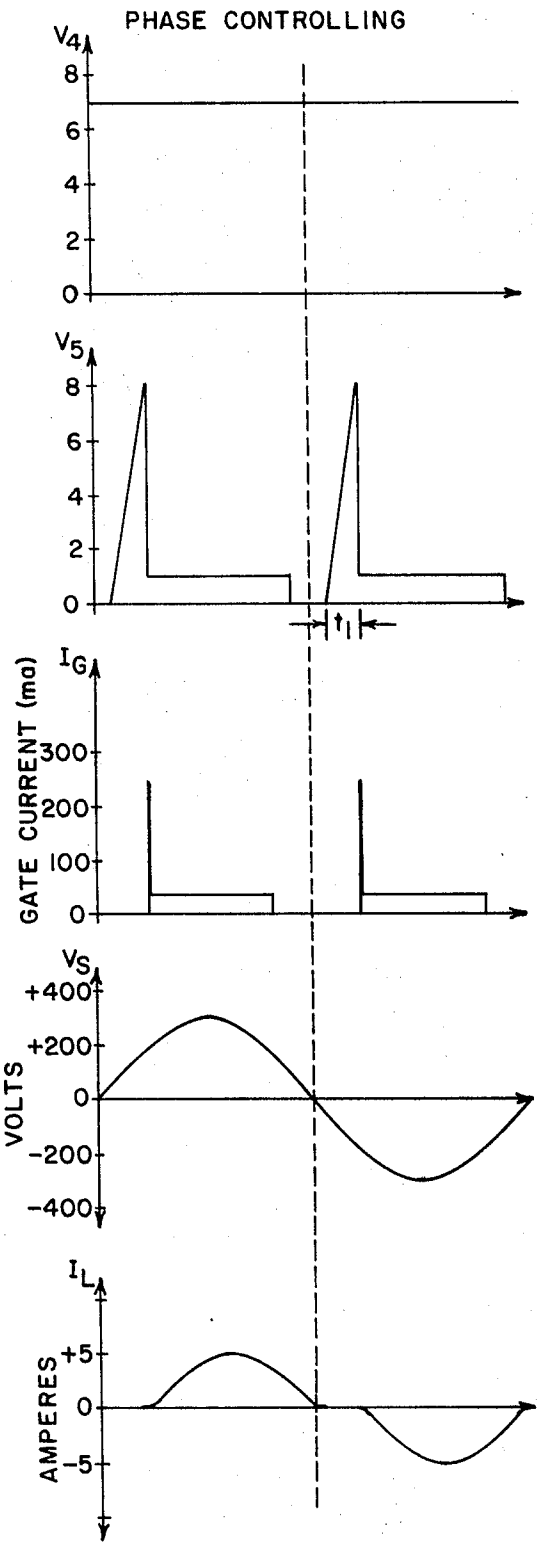


FIG. 14A.

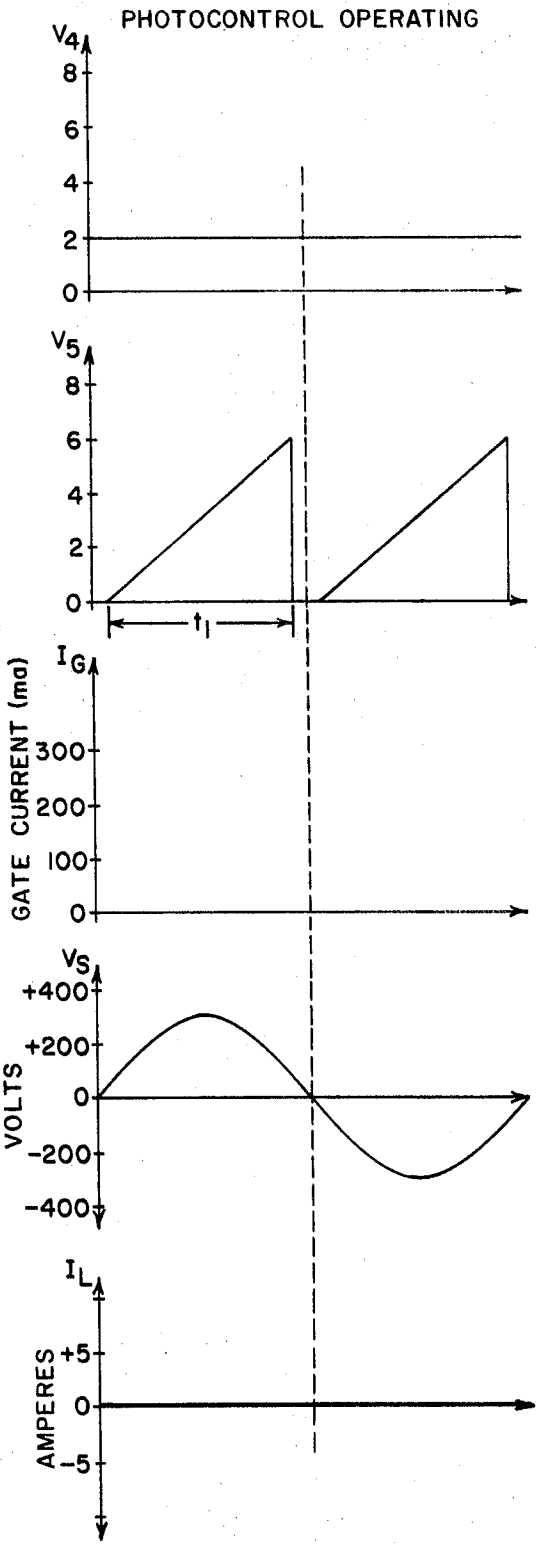


FIG. 14B.

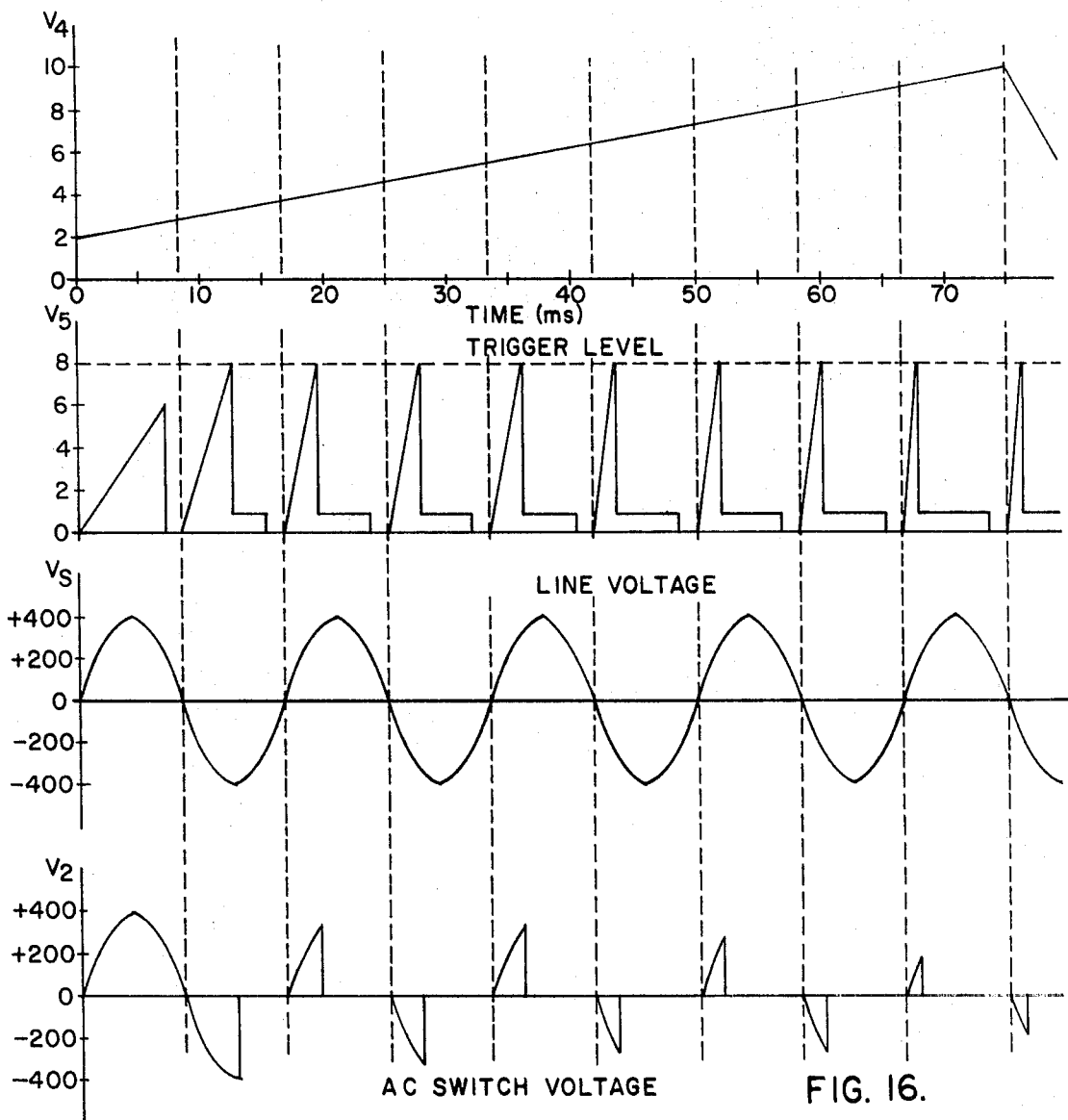


FIG. 16.

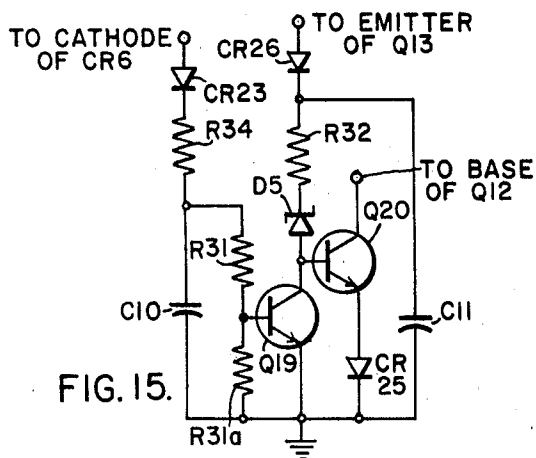


FIG. 15.

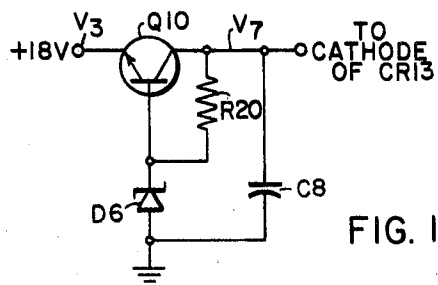


FIG. 17.

PHASE-CONTROLLED UNIVERSAL BALLAST FOR DISCHARGE DEVICES

CROSS-REFERENCES TO RELATED APPLICATIONS

In copending application Ser. No. 807,710, filed concurrently herewith by Joseph C. Engel, Robert T. Elms and George A. Kopenhagen, and owned by the present assignee, now U.S. Pat. No. 3,519,881 is disclosed a starting and operating apparatus which facilitates starting and operation of discharge lamps having different starting and operating characteristics. This apparatus applies to the lamp a very high voltage pulse, which is followed by an intermediate voltage, high energy pulse. Such an apparatus is particularly adapted to be used in conjunction with the apparatus of the present invention.

In copending application Ser. No. 807, 711, filed concurrently herewith, by Joseph C. Engel, and owned by the present assignee, and now abandoned is disclosed a solid-state photocontrol apparatus which eliminates the use of movable contacts which are subject to wear and failure. Such a photocontrol apparatus is particularly adapted to be used in conjunction with the apparatus of the present invention.

BACKGROUND OF THE INVENTION

The usual discharge device operates with a negative volt-ampere characteristic and some form of current limiting ballasting is required to prevent a runaway discharge. In recent years there have been developed several new types of discharge devices which have achieved some limited commercial success for applications such as outdoor flood lighting and similar uses, and these discharge devices have promise for use in interior lighting. Such devices are commercially marketed under various trade designations, but broadly can be categorized as mercury-metal halide, high-pressure, discharge devices and sodium or mercury-sodium discharge devices which utilize a light-transmitting refractory envelope formed of polycrystalline alumina or similar material. Various combinations of such devices are also known. These devices, together with the well-known high-pressure mercury-vapor discharge devices, are used for high-bay factory lighting, highway and floodlighting, and stadium lighting to name a few of the applications.

One of the problems with the use of such discharge lamps is that each type has different voltage and operating characteristics, even though the wattage ratings might be the same. The effect of this is that each type of lamp requires a different ballast which is specially tailored to start and operate the lamp. The problem is further complicated by the fact that in the field of mercury-metal halide lamps, a myriad of different metal-halide additives can be used to achieve different illumination effects, and each different combination of metal halide additives often changes the lamp starting and operating characteristics sufficiently to require a different lamp starting and operating ballast. Since the ballast represents a substantial portion of cost of the fixture, once the user is committed to one specific type of lamp, he cannot readily change lamp types without incurring substantial expense in changing the lamp starting and operating ballast.

It is known in the art to ballast a discharge device by actuating a bilateral switch to vary the input to a lamp so that the average lamp input is maintained at about a predetermined value. Such an apparatus is disclosed in U.S. Pat. No. 3,222,572 dated Dec. 7, 1965. In this disclosed apparatus, the bilateral switch is actuated by sensing a lamp operating condition, such as current or brightness. Such an apparatus is designed to be operable with only one specific type of lamp which has predetermined voltage and current and operating characteristics. A circuit which functions in a generally similar fashion is disclosed in U.S. Pat. No. 3,265,930 dated Aug. 9, 1966.

In U.S. Pat. No. 2,486,068 dated Oct. 25, 1949 is described a tube-type wattmeter as well as a circuit which can effect multiplication and division of independent quantities. More recently, semiconductor circuits which function in a similar fashion have been disclosed in U.S. Pats. Nos. 3,152,250 dated Oct. 6, 1954 and 3,197,626 dated July 27, 1965.

SUMMARY OF THE INVENTION

It is the general object of the invention to provide a ballast apparatus for starting and operating any of a plurality of discharge devices having varying voltage and current operating characteristics.

It is another object to provide a ballast apparatus which can be readily and easily modified to operate lamps having different wattage ratings, as well as varying voltage and current operating characteristics.

It is a further object to provide a ballast apparatus which is readily adapted to have a solid-state photocontrol operate in conjunction therewith.

It is an additional object to provide a ballast apparatus which is independent of line voltage variations and which continuously monitors lamp wattage and regulates the average lamp power in a closed loop system.

It is yet another object to provide a ballast apparatus which is of solid-state design and can supply a lamp voltage in excess of instantaneous line voltage to facilitate operation of different types of lamps.

It is still another object to provide a solid-state universal type of ballast which regulates lamp current to a maximum permissible value during the lamp warmup to limit the warmup time required.

The foregoing objects of the invention, and other objects which will become apparent as the description proceeds, are achieved by providing a ballast apparatus which comprises an impedance means, preferably an inductor, connected between the input terminals and output terminals of the apparatus, along with a semiconductor switch. The switch is responsive to a control signal to close and the relative proportion of time the switch is closed determines the average wattage consumed by an operating lamp which is connected across the output terminals. A solid-state-wattmeter has a voltage-responsive input portion which continuously generates a varying signal which is proportional to the voltage developed across the operating lamp, and the wattmeter also has a current-responsive input portion which continuously generates a varying signal which is proportional to the current through the operating lamp. These signals are combined to produce a signal which is proportional to the logarithm of their product. The logarithmic signal is then converted to a varying signal which varies in accordance with the antilogarithm of the logarithmic signal and the antilogarithmic signal is then averaged to provide a composite signal which varies in accordance with the average wattage consumed by the operating lamp. This averaged composite signal actuates a control signal generator which in turn actuates the closing of the semiconductor switch in order to maintain the average wattage of the operating lamp at about its predetermined desired value.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention, reference is made to the accompanying drawings wherein:

FIG. 1 is a block diagram of the present ballast apparatus;

FIGS. 2A and 2B show a detailed comprehensive circuit diagram of the present ballast;

FIGS. 2C and 2D correspond to FIGS. 2A and 2B with the specific values of the circuit components shown;

FIG. 3 is a graphic representation of voltage vs. time setting forth the line voltage and lamp voltage relationships encountered during operating conditions;

FIG. 4 is a circuit diagram of the voltage-responsive input portion of the semiconductor wattmeter portion of the apparatus with the various current relationships shown thereon;

FIG. 5 is a circuit diagram of the current-responsive input portion of the semiconductor wattmeter portion of the apparatus with the various current relationships shown thereon.

FIG. 6 is a circuit diagram of the constant current generator used to provide a constant current signal for use with the semiconductor wattmeter.

FIG. 7 is a circuit diagram of the multiplier section of the wattmeter wherein the varying current signal and varying voltage signal are multiplied and then averaged;

FIG. 8 is a circuit diagram of the logic and timing circuit which constitutes a part of the control signal generating means for triggering the semiconductor switching means;

FIG. 9 is a graph of voltage vs. both current and time illustrating the phase sequence relationships used to trigger the semiconductor switch;

FIG. 10 is a circuit diagram of the gate drive portion of the signal generating means which controls the switching means;

FIG. 11 is a circuit diagram of the zero voltage reset which operates with the logic and timing circuit to insure that the AC switch is turned off at the start of each half cycle;

FIG. 12 is a circuit diagram of the lamp warmup current regulator;

FIG. 13 is a circuit diagram of the solid-state photocontrol which is particularly adapted to be operated with the present ballast;

FIGS. 14A and 14B are graphs of the ballast operating characteristics wherein voltage and current relationships are plotted vs. time showing the operation with the photocontrol actuated and the photocontrol not actuated;

FIG. 15 is a circuit diagram of the high voltage pulse recycler used to start a sodium-mercury high-pressure discharge device;

FIG. 16 is a graph of voltage vs. time setting forth the various relationships present when starting a sodium-mercury high-pressure discharge lamp from the present apparatus; and

FIG. 17 is a circuit diagram of the low-voltage regulator of the present apparatus.

DESCRIPTION OF THE PREFERRED EMBODIMENT

As noted hereinbefore, present conventional ballasting techniques for controlling present day high-pressure vapor lamps require a specially designed ballast for each type of lamp. The ballast of the present invention will operate all types of such lamps at a predetermined power rating with no changes in the circuitry, with the operation being independent of line voltage variations since the lamp wattage is maintained substantially constant. All that is required is to replace a lamp of one type with a lamp of a different type and the present ballast will automatically compensate for the different voltage and current operating characteristics. In addition, some types of lamps change their operating characteristics throughout their life. The present ballast automatically compensates for such changes and maintains the desired lamp wattage constant.

The basic block diagram of the present ballast apparatus is shown in FIG. 1, and each of the blocks will be explained separately in the following discussion. FIGS. 2A-2D set forth a circuit diagram of the complete ballast and each component thereof will be described in detail. In the diagram in FIGS. 2A-2D, all resistors are 0.5 watt unless otherwise marked, capacitors are 30 volt unless otherwise marked, transistors are NPN 2N1711 and PNP 2N2905 unless otherwise designated, and diodes are 1N457 unless marked.

POWER CIRCUITRY

This circuitry is shown in FIGS. 2A and 2C and comprises a 5A, 600 volt AC switch, S, C1a, C1, C13, C14, R5, R35, L₁ and L₂. This circuit functions as follows. Because the specific ballast is designed to operate a 400 w. lamp 10 connected across output terminals 12 and 14, from a 210 to 270 volt AC line to which the input terminals 16 and 18 are adapted to be connected, a 5 ampere, 600 switch is used. Inductor L₂ is

selected to yield the required lamp current for either the highest voltage lamp at the lowest line or the lowest voltage lamp at the lowest line, whichever produces the lowest value of inductance. This inductor normally will be about 27 ohms at 60 Hz.

Resistor R5 and capacitor C1 are used to limit the rate at which the voltage across the AC switch rises and this prevents dv./dt. turn-on of the AC switch. The switch has a dv./dt. rating in excess of 20 volts/microsecond. Winding 1-2 of L₂ and capacitor C13 are used to produce a high voltage pulse across the lamp 10. When the AC switch first turns on, C13 is at 0 volts. Thus for (+) values of line voltage, the total line voltage appears across winding 1-2. At this instant of time the voltage across winding 2-3 is:

$$V_s \left(\frac{N_{2-3} \text{ number of turns in } 2-3}{N_{1-2} \text{ number of turns in } 1-2} \right) = V_{2-3}, \text{ wherein}$$

V_s = instantaneous value of line voltage when AC switch turns on. A representative value for this starting pulse is 2500 volts.

Network C14, L₁, L₂ and R35 provide the capability to supply a lamp voltage in excess of the instantaneous line voltage when the AC switch first turns on during lamp operation. In explanation, when the AC switch is first turned on, C14 is at a low voltage due to the discharging action of R35. Thus all the line voltage is applied across L₁ and L₂. If the lamp is not in a low impedance state, L₁, L₂ and C14 form a series LC circuit which is underdamped. Under these circumstances the voltage across C14 can rise to almost twice the instantaneous line voltage, as shown in FIG. 3. This voltage pulse is sufficient to cause an operating lamp to strike each half cycle and go into a low impedance state. This basic operating circuit is described more fully in the aforementioned copending application Ser. No. 807,710, filed concurrently herewith, now U.S. Pat. No. 3,519,881. C_{1a} provides power factor correction. Zener diodes D_{1a} and resistor R_{1a} protect the AC switch S from excess voltage transients.

TRANSISTORIZED WATTMETER

The wattmeter comprises C₃, CR1, CR3, CR5, CR6, CR7, CR8, CR9, D₁, D₃, Q₁, Q₂, Q₃, Q₆, Q₇, Q₈, Q₉, R₁, R₂, R₃, R₄, R_{4a}, R₉, R₁₄ and R₃₆. Since the wattmeter is essentially a current operated device, currents proportional to instantaneous lamp current and voltage are provided. The circuit in FIG. 4 provides a current proportional to instantaneous lamp voltage |V₁|. This circuit constitutes a voltage-responsive wattmeter input portion which continuously generates a varying signal which is proportional to the varying voltage developed across the lamp 10 as operated. By way of further explanation, when V₁ is positive I₁₁ is equal to I₂ and both are proportional to V₁/(R₃+R₃₆). Under these conditions, CR3 is forward-biased and both Q₁ and Q₂ are in a nonconducting state. When V₁ is negative I₁₃ is equal to -V₁/(R₃+R₃₆) which is equal to |V₁|/(R₃+R₃₆) since -V₁=|V₁| at this time. Since Q₁ has a high beta, I₁₃ is equal to I₁₄. Current I₁₅ equals

$$-I_{14} \left(\frac{R_1}{R_2} \right)$$

since the diode drop of CR1 cancels out the emitter-base junction drop of Q₂. Also, I₁₅ is equal to I₂ since CR3 is now reverse-biased. Thus, for negative values of V₁, I₂ is equal to

$$\frac{|V_1|}{R_3 + R_{36}} \times \frac{(R_1)}{R_2} = \frac{|V_1|}{R_3 + R_{36}}$$

since R₁=R₂. As a result,

$$I_2 = \frac{|V_1|}{R_3 + R_{36}}$$

for all values of V₁ and when the AC switch S is conducting, V₁=A-lamp. Thus the circuit as shown in FIG. 4 is essentially a full wave rectifier wherein I₂ is proportional to the magnitude of V_L, wherein V_L represents the instantaneous voltage drop across the operating lamp 10.

Current proportional to load current is provided by the circuit shown in FIG. 5. This circuit comprises a current-responsive wattmeter input portion which continuously generates a varying signal which is proportional to the varying current (I_L) through an operating lamp 10.

Current transformer T_1 steps down the load current such that $I_{17}=I_L/100$. Diode bridge CR5, CR6, CR7 and CR8 full wave rectify I_{17} so that $I_{18}=|I_{17}|$. Components CR9, Q_6 , R_9 and R_{14} form a current divider. The result is that I_1 is equal to

$$\left(\frac{R_9}{R_{14}+R_9} \right) I_{18}$$

when the voltage across CR9 cancels the voltage across the base-emitter junction of Q_6 . Thus, current $I_1=K_1|I_L|$ where $K_1=9/100(R_{14}+R_9)$. The circuit shown in FIG. 5 is a full wave current sensor wherein I_1 is proportional to the magnitude of the lamp current. If the circuit is designed to operate a lamp 10 with a predetermined wattage of 400 watts, the resistor R_{14} has a resistance of $\approx 10,000$ ohms. This value of resistance can be preselected to vary the average current, and thus the power, at which the lamp 10 is to be operated. Alternatively, R_{14} can be provided with a series of taps so that the wattage at which the lamp 10 will operate can be readily varied to accommodate a plurality of lamp types which are designed to operate at different wattages.

The constant current generator is shown in FIG. 6 and provides a bias for Q_7 . The collector current I_{16} , of Q_5 is maintained constant in the following manner. The voltage of D_1 appears across R_7 , and the emitter current of Q_3 is

$$\frac{V_{D_1}}{R_7} = \frac{4.7v}{4.7K} = 1 \text{ ma.}$$

Neglecting the base current of Q_3 its collector current will then be 1 ma. and is independent of the supply voltage. This constant current represents the power reference signal as will be discussed hereinafter.

The multiplier portion of the wattmeter circuit is shown in FIG. 7. The current I_1 in Q_6 is proportional to the magnitude of the instantaneous lamp current and the current I_2 is proportional to the magnitude of the instantaneous lamp voltage when the AC switch is "on." Since the external drains on the collector current of Q_3 are negligible, the current I_3 in Q_9 is equal to the constant current I_{16} . Owing to the exponential relationship between voltage and current in a forward-biased diode, the product of the currents in Q_6 and Q_9 is proportional to the product of the currents in Q_7 and Q_9 . Thus the current in Q_7 is proportional to the instantaneous value of lamp power. Capacitor C_3 filters this current so that the average current drawn by the collector of Q_7 is proportional to average load power. The voltage V_4 is equal to the difference of I_{16} minus I_3 (average) times the input impedance ($R_{IN} \approx 120K$) of the reset of the circuitry connected to that diode. This is true for a range of V_4 voltages from 1 to about 10.5 volts. At 10.5 volts Zener D_3 starts to conduct and clamps V_4 . Thus, for the foregoing voltage range, each voltage corresponds to a range of powers. This range is determined by the accuracy of the wattmeter which is about 1 percent. To illustrate if V_4 is 5 volts and the nominal power for 5 volts is 400 watts, then lamp power will be 400 w. ± 1 percent when $V_4=5$ volts. Briefly, summarizing the circuit as shown in FIG. 7, the varying signal outputs of the voltage-responsive wattmeter input portion (FIG. 4) and the current-responsive wattmeter input portion (FIG. 5) are combined to generate a varying electric signal (i.e., the voltage across the collector and emitter of serially connected Q_6 and Q_9) which represents the logarithm of the product of the varying signal outputs. This logarithmic signal is fed into the wattmeter output section to generate a signal (the current in Q_7) which varies according to the antilogarithm of the varying logarithmic signal. The wattmeter output section also includes a signal averaging means for averaging the antilogarithmic signal to produce a composite signal (V_4) which represents the average wattage input to the operating lamp 10 with reference to a desired average

wattage. Also, the "average wattage" composite signal V_4 is actually averaged over several half cycles of energizing potential.

LOGIC, TIMING CIRCUIT

The timing circuit shown in FIG. 8 consists of components C_5 , CR10, D_4 , Q_5 , Q_{13} , Q_{14} , Q_{16} , R_{11} , R_{12} , R_{15} , R_{21} , R_{22} , R_{24} and R_{29} . The current I_8 in R_{22} is equal to V_4 less a diode drop divide by R_{22} or approximately V_4/R_{22} . Since Q_{13} has a high beta (about 100), $I_7=I_8$. The voltage across CR10 cancels the base emitter voltage of Q_5 , and the voltage across R_{11} and the combination D_4 , R_{15} is $R_{12}I_7$. The current I_8 therefore equals $(R_{12}/R_{11}) I_7$ and the current I_9 is zero for $R_{12}I_7$ values less than the Zener voltage. For $R_{12}I_7$ values greater than the Zener voltage,

$$I_8 = \frac{R_{12}I_7 - V_{D_4}}{R_{15}}$$

Current I_{10} is approximately equal to I_8 plus I_9 . Thus for each DC voltage V_4 , there is a unique value of current I_{10} , see FIG. 9. Current I_{10} flows into C_5 (Q_{14} and Q_{16} are "off" as will be described hereinafter) causing the voltage V_3 on capacitor C_5 to rise linearly. When V_3 reaches about 8 volts the trigger circuit Q_{14} , Q_{16} , R_{24} and R_{29} trips in the following manner. At 8 volts, the reverse-biased base-emitter junction of Q_{14} avalanches permitting a current to flow into the base of Q_{16} . This base current allows Q_{16} to draw collector current through the base Q_{14} and regenerative turn-on occurs. Transistor Q_{14} and Q_{16} are not turned off until V_3 is reduced to less than a volt or reset to zero. FIG. 9 illustrates a plot of the time necessary for C_5 to charge up to the trigger voltage with respect to the wattmeter output voltage V_4 . Resistors R_{24} and R_{29} prevent Q_{14} and Q_{16} from operating in an open base condition. In summary, the charging rate of C_5 controls the time at which the trigger circuit trips, with the greater the average wattage input to the operating lamp 10, the later the tripping time, and vice versa. The logic-timing circuit, together with the gate drive and zero voltage reset, as described hereinafter, constitute a control signal generating means which is actuated by the composite signal output of the wattmeter means to generate a controlling signal for closing the AC switch. This varies the proportion of time the AC switch is closed in accordance with whether the composite averaged signal from the wattmeter indicates an average wattage input to the operating lamp 10 as that wattage desired, or greater or less than that wattage desired, so that the average wattage input to the operating lamp 10 is maintained at about its predetermined desired value, for example, 400 watts.

GATE DRIVE

Components C_6 , C_{12} , CR15, CR16, CR17, CR18, Q_{17} , R_{10} , R_{23} and R_{33} form the gate drive circuit shown in FIG. 10. Capacitor C_6 is charged up to about 9 volts by transformer T_2 . When the trigger circuit Q_{14} and Q_{16} turn on, base drive is applied to Q_{17} causing Q_{17} to saturate. With Q_{17} saturated all the voltage across C_6 is applied to the R, RC network C_{12} , R_{10} , R_{33} and the gate cathode junction of the AC switch. This voltage causes a current to flow out of the gate of the AC switch. This current has an initial peak value of about 4 times the DC value for about 5 to 10 microseconds. The DC drive current is equal to the voltage across C_6 less the cathode to gate voltage of the AC switch, divided by R_{10} . Gate current is applied while Q_{14} and Q_{16} are "on." When C_5 and the trigger circuit are reset, gate drive is removed. Resistor R_{23} improves the turnoff characteristic of Q_{17} and prevents Q_{17} from operating in an open base condition.

SYNCHRONIZING OR ZERO VOLTAGE RESET

Since the AC switch is required to be turned on at a specific time in each half cycle, capacitor C_5 must be reset at a specific time in each half cycle. Moreover, resetting must occur before the current in the AC switch goes to zero or the AC switch will

not turn off. In order to satisfy the above requirements, resetting of C_5 is chosen to occur at line voltage zero. This provides a very stable reference which will occur before current zero because of the inductive nature of the power circuitry. This function is performed by components C_7 , $CR13$, $CR14$, Q_{15} , Q_{18} , R_{25} , R_{26} , R_{27} , and R_{28} , as shown in FIG. 11. Resistors R_{25} , R_{27} and R_{28} divide the voltage V_8 , which is an unfiltered full-wave rectified sine wave, and apply about one-third of V_8 to the base of Q_{15} . As long as V_8 is above about 3 volts, Q_{15} will be conducting and all the current in R_{26} will flow into the collector of Q_{15} . When V_8 is below about 3 volts, Q_{15} will become nonconducting and the current in R_{26} will be allowed to flow through $CR14$ into the base of Q_{18} . When Q_{18} receives base drive, current is allowed to flow from C_5 through R_{21} into the collector of Q_{18} to ground. This current flow decays the voltage across C_5 to zero in about 200 microseconds. Thus, every time the line voltage goes to zero, Q_{18} resets the voltage of C_5 to zero. Capacitor C_7 is used to filter out voltage transients appearing on the line.

WARMUP CURRENT REGULATOR

Due to the universal nature of the present phase-controlled ballast, the inductor reactance is sufficiently low (about 27 Ω) that during lamp warmup, it would normally pass too much current (about 10A for a 400 watt lamp) at high line voltage. For this reason the logic is designed to maintain the lamp current at a preselected maximum value until the logic begins to regulate power. Components C_2 , C_9 , $CR4$, $CR24$, $D2$, $D7$, R_8 , R_{13} , R_{30} and Q_4 as shown in FIG. 12 perform this regulating function. The voltage V_9 at the cathode of CR_6 is equal to $|I_L| (R_9/100)$, assuming $R_{14} \gg R_9$ (see the description of the transistorized wattmeter). Once this voltage rises above the knee voltage of D_2 , any further increase in this voltage V_9 must appear across R_8 . The voltage across R_8 causes Q_4 to conduct a current I_{19} through R_{13} . Current I_{19} causes voltage V_4 to decrease, and as shown in FIG. 9, a decrease in V_4 causes the ballast to phase-back or reduce the conduction time. If the conduction time is reduced, the average voltage across L_2 is reduced and thus I_L is reduced. Phasing-back continues until an equilibrium condition of the warmup current regulator occurs in which the peak current is reduced to the point where it is just sufficient to enable Q_4 to conduct such current as required to maintain V_4 constant at the particular equilibrium value. Capacitor C_9 is used to provide additional filtering of V_4 and components $CR24$ and R_{30} are used to isolate C_9 from the wattmeter circuitry when the operating lamp 10 is stabilized and current control is no longer needed. Thus the warmup current regulator is connected to the current responsive wattmeter input portion and also to the output section of the wattmeter. When a maximum predetermined current through the lamp 10 is sensed, a bypass impedance decreases the composite signal output of the wattmeter and limits the maximum current which can pass through the operating lamp 10 during warmup. With this warmup circuit, a typical time required for warmup of the operating lamp 10 is about 20 percent of the total time required with usual lamp ballasts.

PHOTOCONTROL

A ballast which is intended for such applications such as street lighting must automatically turn on at an ambient light level of about 1 foot-candle and turn off at an ambient light level of about 5 foot-candles. Shown in FIG. 13 is the photocontrol circuit which performs this function. This circuit consists of components C_4 , $CR11$, $CR12$, Q_{11} , Q_{12} , R_{16} , R_{17} , R_{18} , R_{19} and photocell R_λ . If the ambient light level is below 1 foot-candle the photocell resistance is high causing base drive to flow into Q_{12} . If Q_{12} is "on," then Q_{11} is "off" and the ballast is phase controlling as shown in FIGS. 14A and 14B. When the illumination level rises to 5 foot-candles, the photocell resistance has dropped to such a low value (about 7000 ohms) that Q_{12} is starved of base drive and is turned "off." With Q_{12} "off," Q_{11} receives base drive and is turned "on." When Q_{11} is

"on," voltage V_4 is reduced to about 2 volts and at this level the gate of the AC switch does not receive drive current. With no gate drive to the AC switch the ballast is "off." The ballast turns on again when the illumination level drops to about 1 foot-candle. At this level the photocell resistance is about 15,000 ohms and Q_{12} is turned "on" causing Q_{11} to become nonconducting. The following formulas can be used to calculate R_λ at the two switching points:

Ballast turn-on:

$$V(\text{emitter } Q_{12}) = \left(\frac{R_{18}}{R_{16} + R_{18}} \right) (I_{16} + R_{16} + 18v. - V_{CR11} - V_{BEQ_{11}}) \\ = (18v. - V_{CR12}) \left(\frac{R_\lambda}{R_{17} + R_\lambda} \right) + V_{CR12} - V_{BEQ_{12}}$$

Ballast turn-off:

$$V(\text{emitter } Q_{12}) = \left(18v. \frac{R_{18}}{R_{16} + R_{18}} \right) \\ = (18v. - V_{CR12}) \left(\frac{R_\lambda}{R_{17} + R_\lambda} \right) + V_{CR12} - V_{BEQ_{12}}$$

The foregoing photocontrol is generally described in the aforementioned copending application Ser. No. 807,711, filed concurrently herewith, now abandoned.

HIGH VOLTAGE PULSE RECYCLER

The high-pressure sodium-mercury lamp is the most difficult to start. In order to strike such a lamp, the ballast should produce a series of 2500 to 4000 volt pulses of a 10 to 2 microseconds duration until the lamp is struck. The circuit performing this function is shown in FIG. 15 and is constructed from components C_{10} , $CR25$, $CR26$, D_5 , Q_{19} , Q_{20} , R_{31} , R_{32} and R_{34} . When the illumination level drops sufficiently for the photocontrol to switch the ballast to the "on" state, V_4 immediately starts rising towards 10.5 volts at a rate of about 0.1 v./ms., as shown in FIG. 16. As V_4 rises, the AC switch turns on at a different phase angle each cycle (see FIG. 16). Every other time the AC switch turns on, a pulse of voltage is produced across the lamp. Each voltage pulse is equal to about 11 times the instantaneous line voltage at that time. These pulses occur only on the (+) half cycle as was discussed in the section POWER CIRCUITRY. If, however, the lamp does not strike before V_4 reaches 10.5 volts, V_4 is reset to about 2 volts and recycled to 10.5 volts. Voltage V_4 should be reset due to the fact that when $V_4 = 10.5$ v., the voltage pulse across the lamp is less than 1000 volts. Resetting occurs when V_4 reaches about 10v., the voltage across C_{11} rises to about 9.5 v. and D_5 starts to conduct. The current in D_5 flows through R_{32} into the base of Q_{20} . This base current causes Q_{20} to conduct the current in R_{17} away from the base of Q_{12} resetting the photocontrol to the "off" state. With the photocontrol in the "off" state, Q_{11} is "on" state. With the photocontrol in the "off" state, Q_{11} is "on" and V_4 decays down to about 2 volts. When V_4 drops to about 2 volts the photocontrol changes to the "on" state and V_4 starts rising towards 10.5 volts. This recycling continues until the lamp strikes. When the lamp is struck, its current produces a voltage of about 12 volts peak across R_9 . This 12 volt peak charges C_{10} to 12 volts and causes about 30 μ a to flow through R_{31} into the base of Q_{19} . Transistor Q_{19} is thus turned "on" and all the current in R_{32} flows into the collector of Q_{19} . Under these conditions, Q_{20} does not receive base drive and the photocontrol is no longer reset to the "off" state. The lamp current is then regulated by the warmup current regulator until the wattmeter starts to regulate power.

LOW VOLTAGE REGULATOR

The voltage regulator circuit shown in FIG. 17 consists of components C_8 , D_6 , Q_{10} and R_{20} . The voltage V_7 on C_8 can range anywhere from 20 to 40 volts depending on the line voltage and the turns ratio of transformer T_2 . This voltage is then applied across the series circuit R_{20} , D_6 . Due to Zener action the voltage across D_6 is regulated to 19 volts. Since the base of Q_{10} is connected directly to D_6 , the base voltage of Q_{10}

must also be 19 volts. Since the emitter of Q_{10} can be only about 1 volt below the base of Q_{10} , V_3 is thus regulated to 18 v.

It will be recognized that the objects of the invention have been achieved by providing a ballast apparatus for starting and operating any of a plurality of different discharge devices having varying voltage and operating characteristics. If desired, the wattage at which the lamps will operate can readily be modified to accommodate different lamp types. The ballast apparatus is readily adapted to operate in conjunction with a solid-state photocontrol.

As an alternative embodiment, the main AC switch could be paralleled by an inductor which would supplement the series inductor to vary the value of impedance, when the switch is open and closed, between two finite values. Also, the switch and series-connected inductor can both be paralleled by an inductor.

In further explanation of the operation of the photocontrol circuit as shown in the graphs of FIGS. 14A and 14B, as related to the block diagram as shown in FIG. 1, when the resistance of the photocell is low, as is the case during daylight hours, the voltage across V_4 drops to about 2 volts and the photocell "operates" to keep the circuit in an "off" condition. The voltage across V_3 never reaches the 8 volts required to trigger Q_{14} and Q_{16} , as shown in FIG. 8. In such case, as shown in FIG. 14B, the gate current I_G will always be "zero," and the lamp current I_L will be "zero." The supply voltage V_S remains the same. When the photocontrol is "not operating," which permits the apparatus to be in an "on" condition the apparatus is phase controlling, as shown in FIG. 14A. In this case, when V_3 reaches about 8 volts, Q_{14} and Q_{16} , see FIG. 8, are triggered, which in turn causes the gate current I_G to flow to the switch S. Lamp current I_L then flows and the supply voltage V_S of course remains constant.

In further explanation of the operation of the starting of a sodium-mercury type lamp, as shown in the graphs of FIG. 16 and as related to the block diagram shown in FIG. 1, if the lamp does not strike initially, the pulse recycler causes V_4 again to rise to 10 volts over a period of many cycles thereby varying the time in each cycle that V_3 reaches the trigger level to turn on the AC switch "S," with the representative voltages which appear across the switch "S" shown as V_2 in FIG. 16. This recycling is repeated until the lamp 10 is struck.

We claim as our invention:

1. An apparatus for ballasting any of a plurality of discharge devices having varying voltage and current operating characteristics in order to operate a ballasted device at about a predetermined wattage rating, said apparatus comprising:

- a. output terminals adapted to have connected thereacross any of said discharge devices, and input terminals adapted to be connected across a source of energizing potential;
- b. impedance means forming a part of said apparatus to limit the maximum current therethrough;
- c. semiconductor switching means connected between said input terminals and said output terminals and having a high impedance open position and a low impedance closed position, said semiconductor switching means responsive to a control signal to effect a closing of said semiconductor switching means, and the relative proportion of time said semiconductor switching means is closed varying the average wattage consumed by an operating device connected across said output terminals;
- d. wattage-measuring means comprising a semiconductor wattmeter, said wattmeter having a voltage-responsive input portion connected in said apparatus to continuously generate a varying signal which is proportional to the varying voltage developed across said operating device, said wattmeter having a current-responsive input portion connected in said apparatus to continuously generate a varying signal which is proportional to the varying current through said operating device, means for combining said varying signal outputs of said voltage-responsive input portion and said current responsive input portion to

generate a varying electric signal which represents the logarithm of the product of said varying signal outputs, said wattmeter having an output section into which said varying logarithmic signal is fed to generate a signal which varies according to the antilogarithm of said varying logarithmic signal, and said wattmeter output section including a signal-averaging means for averaging said varying antilogarithmic signal to produce a composite signal having a magnitude which varies in accordance with the average wattage input to said operating device; and

e. control signal generating means electrically connected to said wattage-measuring means and said switching means to receive and be actuated by said composite averaged signal from said wattage-measuring means and to generate a controlling signal for closing said switching means, said controlling signal varying the relative proportion of time said switching means is closed in accordance with whether said composite averaged signal from said wattage-measuring means indicates an average wattage input to said operating device as equal to that wattage desired, or greater than or less than that wattage desired, to maintain the average wattage input to said operating device at about its predetermined desired value.

2. The apparatus as specified in claim 1, wherein said input terminals are adapted to be connected across a source of AC energizing potential, said impedance means is an inductor, said switching means is an AC switch, and said control signal generating means generates a controlling signal in response to said composite averaged signal from said wattage-measuring means once each half cycle of energizing AC potential.

3. The circuit as specified in claim 2, wherein said wattage-measuring means measures the wattage input to said operating device throughout each half cycle of AC energizing potential, said composite signal output of said wattage-measuring means comprises a continuing series of signals each succeeding half cycle of AC energizing potential with each signal representing the average wattage input to said operating device during several half cycles of energizing potential, and said control signal generating means is actuated by said composite average signal from said wattage-measuring means during each half cycle of AC energizing potential.

4. The circuit as specified in claim 3, wherein said semiconductor AC switching means is gate controlled and is gated to a closed position by said controlling signal from said control signal generating means once during each half cycle of AC energizing potential.

5. The circuit as specified in claim 4, wherein said semiconductor switching means is gated to a closed position at varying times during each half cycle of energizing potential, said semiconductor switching means being gated to a closed position in a later portion of a half cycle when said composite averaged signal indicates an average wattage input to said operating device greater than desired, and said semiconductor switching means being gated to a closed position in an earlier portion of a half cycle when said composite averaged signal indicates an average wattage input to said operating device less than desired.

6. The apparatus as specified in claim 5, wherein said control signal generating means comprises a timing circuit and a trigger circuit, said timing circuit connected to the output of said wattmeter and said trigger circuit connected to the gate of said AC switch, said timing circuit including a capacitor which is charged at a rate which varies with the magnitude of the composite signal output from said wattage-measuring means, the charging rate of said capacitor serving to control the point at which said trigger circuit gates said AC switch, with a greater-than-desired wattage input to said operating device causing said AC switch to be gated at a relatively later period of time in each half cycle of energizing potential, and vice versa.

7. The apparatus as specified in claim 6, wherein each time the AC energizing potential passes through zero, a discharging

circuit is actuated to discharge said capacitor preparatory to being recharged during the next half cycle of energizing potential.

8. The circuit as specified in claim 5, wherein said wattmeter comprises a first transistor having an emitter, base and collector with its base and collector connected, and a second transistor having an emitter, base and collector with its base and collector connected, said transistors connected to each other in series additive relationship, said voltage-responsive input portion of said wattmeter having an output connected across the base and emitter of one of said transistors, said current-responsive input portion of said wattmeter having an output connected across the base and emitter of the other of said transistors, and said serially connected transistors having developed across the unconnected base and emitter thereof a voltage signal which is proportional to the instantaneous value of the log of the product of the current outputs of said voltage-responsive input portion and said current-responsive input portion, an output transistor having an emitter, base and collector, an additional transistor having an emitter, base and collector with the base and collector connected, the base of said additional transistor connected with the emitter of said output transistor, and the base of said output transistor and the emitter of said additional transistor having applied thereacross the voltage output signal of said serially connected transistors, a constant current generator having an output connected to the collector of said output transistor with the resulting current through said output transistor proportional to the instantaneous wattage input to said operating device, and a capacitor connected across the collector and emitter of said output transistor to filter the signal developed thereacross.

9. The apparatus as specified in claim 2, wherein a warmup current regulator for said device is connected to said current-responsive input portion and also to the output section of said wattmeter, said warmup current regulator having a maximum current detector portion which is responsive to a maximum predetermined current passing through said operating device to actuate a signal bypass impedance to decrease the composite signal output of said wattage-measuring means and limit the current which can pass through said operating device during warmup thereof to said predetermined maximum.

10. An apparatus for ballasting a discharge device having

varying voltage and current operating characteristics in order to operate the ballasted device at about a predetermined wattage rating, said apparatus comprising:

- a. output terminals adapted to have connected thereacross said discharge device, and input terminals adapted to be connected across a source of energizing potential;
- b. impedance means forming a part of said apparatus to limit the maximum current therethrough;
- c. switching means connected between said input terminals and said output terminals and having a high impedance open position and a low impedance closed position, said switching means responsive to a control signal to effect a closing thereof, and the relative proportion of time said switching means is closed varying the average wattage consumed by an operating device connected across said output terminals;
- d. wattage-measuring means having a voltage-responsive input portion connected in said apparatus to generate a varying signal which is proportional to the varying voltage developed across said operating device, said wattage-measuring means having a current-responsive input portion connected in said apparatus to generate a varying signal which is proportional to the varying current through said operating device, means for multiplying said varying signal outputs of said voltage-responsive input portion and said current responsive input portion to produce a composite signal having a magnitude which varies in accordance with the average wattage input to said operating device; and
- e. control signal generating means electrically connected to said wattage-measuring means and said switching means to receive and be actuated by said composite signal from said wattage-measuring means and to generate a controlling signal for closing said switching means, said controlling signal varying the relative proportion of time said switching means is closed in accordance with whether said composite signal from said wattage-measuring means indicates an average wattage input to said operating device as equal to that wattage desired, or greater than or less than that wattage desired, to maintain the average wattage input to said operating device at about its predetermined desired value.