RCA
Solid State
Division

Power Transistors
Application Note
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Solid-State Ballasting of Mercury-Arc Lamps

by

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Recent advances in the voltage- and current-handling capabilities of power transistors have made possible the design of solid-state switching-regulator ballasts that offer significant advantages over conventional ballasting devices for high-pressure mercury-arc lighting systems. In addition to the usual transistor-circuit benefits of reduced weight and bulk, the new solid-state ballasts provide unmatched power regulation for line-voltage fluctuations and exceptional versatility. The basic solid-state ballast circuit includes a built-in lamp-dimming feature that permits a single design to be used with lamps of various power ratings over a range of 50 to 150 per cent of the power rating specified for the ballast design. Moreover, transistor ballast circuits eliminate the annoying strobe effect associated with conventional ballasting devices and thereby make the long-life, efficient mercury-arc lamps suitable for use in studios and similar critical lighting areas.

RELATIVE MERITS OF VARIOUS LIGHTING SYSTEMS

Table I compares the characteristics and provides a brief cost analysis of incandescent, fluorescent, mercury-arc, Lucalox,* and sodium-lamp lighting systems. The over-all cost of each system is determined by three main factors: (1) power consumed during operation, (2) replacement and maintenance, and (3) initial installation. The cost of initial installation is almost insignificant when compared to the other cost items. In general, power-consumption costs are approximately seven times greater than the costs of initial installation. Replacement-and-maintenance costs, at present, represent two or three times the initial-installation costs, but are rising at a very rapid rate. Because of the higher efficiency and reduced maintenance requirements of gas-discharge (arc) lamps, lighting systems that use these types of lamps have displaced those that use incandescent (tungsten-filament) lamps in most industrial and highway installations.

Fluorescent lighting systems are currently the most widely used of the various gas-discharge types. In view of the rapid rise in maintenance costs, however, the long-life (approximately 20,000 hours) mercury-arc bulbs have become increasingly attractive. The use of mercury-arc lighting systems is increasing at a rate that far exceeds that of fluorescent systems, and mercury-arc lamps are now being used in numerous applications for which fluorescent types were previously employed, as well as in many new applications in the home. In addition, greater expansion of the application of mercury-arc lamps is expected to result from new phosphors which will further develop the light characteristics of these devices.

Another important consideration in selection of a gas-discharge lighting system is whether the lamp is to be operated from an ac or a dc power source. Neither fluorescent nor Lucalox lamps are particularly well suited for dc operation. When fluorescent lamps are operated from dc voltages, the direct currents force the mercury atoms to one end of the arc tube with a resultant dimming of the other end. Moreover, the lamp efficiency for dc operation may be only 70 per cent of that for high-frequency ac operation, and the life of a dc-operated fluorescent is derated 20 per cent. The Lucalox arc tube cannot withstand the temperature differential between the electrodes that is characteristic of dc operation. This temperature differential results because the positive electrode is disproportionately heated by electron bombardment.

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* Trade name of the General Electric Company

TABLE I – A COMPARISON OF THE CHARACTERISTICS OF VARIOUS LIGHTING SOURCES

Type	Description	Ingredients	Light Quality	Percent Eff.	Life (hrs)	Warmup Time	Time Before Restart	400W Bulb or Equivalent			Cents/ lumen-hr x 10^{-4}
								Bulb Cost	Indoor Fixture Cost	Ballast Cost	
Incandescent	Filament (point light source)	Tungsten in Nitrogen	Good - much red, no blue (continuous spectrum)	2.6	2,000	None	None	$ 1.25	$10.00	-	1.80
Fluorescent	Low-pressure vapor with phosphor correction	Mercury	Good	9.5	10,000	Few Seconds	None	$16.00	$25.00	$ 20.00	0.56
Mercury Arc (Color Corrected)	High-pressure vapor with phosphor correction (point source)	Mercury and Argon in Quartz burner	Slightly cold	7.5	20,000	4 min.	5 min.	$20.00	$30.00	$ 45.00	0.70
Lucalox	High-pressure, high-temperature vapor (point source)	Sodium and Mercury in Alumina burner	Sunny, much yellow	15.0	6,000	3.0 min.	1 min.	$45.00	$30.00	$120.00	0.54
Sodium Vapor	High-pressure vapor (point source)	Sodium, Neon	Yellow monochromatic	15.0	6,000	18 min.	None				

NOTE: In the cost analysis, the maintenance factor proportional to life of bulb was not included. The electrical power cost was assumed to cost three cents per kilowatt hour, and the life of the ballast and fixture was estimated to be 60,000 hours.

High-pressure mercury-arc lamps provide the same efficiency for either ac or dc operation. For dc operation, the mercury-arc lamp offers the advantage of no strobe effect. However, because only one arc-tube electrode is bombarded by electrons during dc operation, a slight decrease in tube life results from the overheating of this electrode. A redesign of the electrodes should alleviate this condition.

CHARACTERISTICS OF MERCURY-ARC LAMPS

Fig.1 shows the basic construction of a mercury-arc lamp. The arc tube is made of quartz to withstand the wide extremes and sharp gradients of temperature to which it is subjected. This quarts tube contains some argon in addition to the mercury which evaporated and ionized to provide the arc lighting. The argon is a starting aid and also prolongs the life of the lamp electrodes by retarding electron bombardment and evaporation of the electrodes.

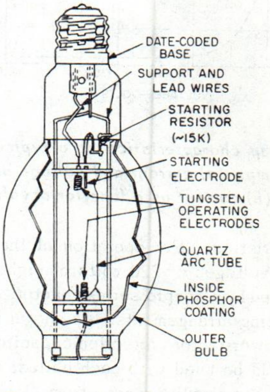


Fig.1 - Cutaway view of a mercury-arc lamp.

A mercury-arc lamp is essentially a varying impedance which is driven from the ac line through an inductive ballast. Fig.2 shows the voltage and current characteristics of the mercury-arc bulb during warmup. The argon in the arc tube ionizes when the voltage across the lamp electrodes rises to 200 volts (point 1 in Fig.2); the voltage then decreases rapidly to 18 volts (point 2 in Fig.2). The lag in current with respect to the bulb voltage, shown in Fig.2(b), results because of the ballasting inductor in series with the lamp electrodes. Warm up of the mercury-arc bulb is completed in approximately 3 minutes. During this period, the mercury vaporizes, and a stable operating point is then attained (point

3 in Fig.2). The inductive ballast is designed so that the slope of the change in voltage between points 2 and 3 results in a reduced warm-up time. If the mercury-arc bulb is turned-off, the mercury cannot be re-ionized until approximately 5 minutes have elapsed, i.e., until the pressure and temperature in the arc tube have decreased sufficiently.

CONVENTIONAL BALLASTING METHODS

For operation of the mercury-arc lamp in 120-volt line applications, a voltage step-up transformer ballast must be used to develop the high starting potential (200 volts) and the required current-voltage slopes [shown in Fig.2(b)]. This transformer ballast, however, must have a large leakage inductance to accommodate the varying bulb characteristics. For operation of the mercury-arc lamp from ac voltages of 220 volts or higher, ballasting may be provided by a simple series reactor. Fig.3 shows the two ballasting arrangements. As shown in the circuit diagrams, a power-factor-correction capacitor (usually an oil type) should be used with each ballast circuit. The efficiency of these circuits ranges from 75 to 95 per cent.

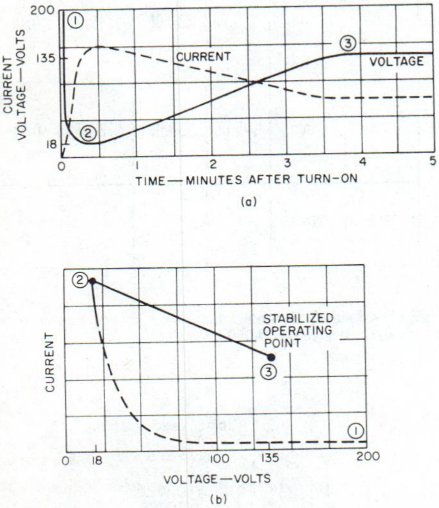


Fig.2 - Warm-up characteristics of a typical (135-volt) mercury-arc lamp: (a) current and voltage as a function time; (b) current as a function of voltage.

A major disadvantage of conventional ballasting reactors is poor power regulation for line-voltage fluctuations. The power regulation can be improved, as shown in Fig.4(a), by use of a saturating (constant-current) type of ballasting reactor. When this type of ballasting is employed, however, circuit efficiency is reduced, and a longer bulb warm-up period is required. Voltage and current waveshapes of conventional ballasts are shown in Fig.4(b).

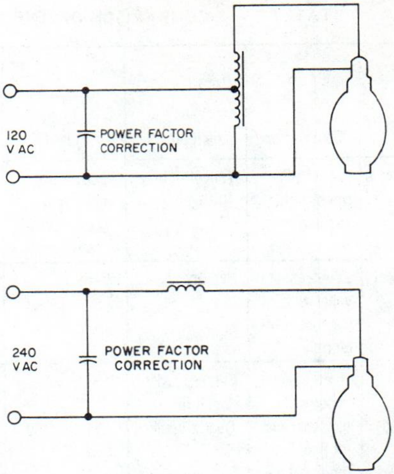


Fig.3 - Conventional ballasts for 120- and 240-volt ac mercury-arc lamps.

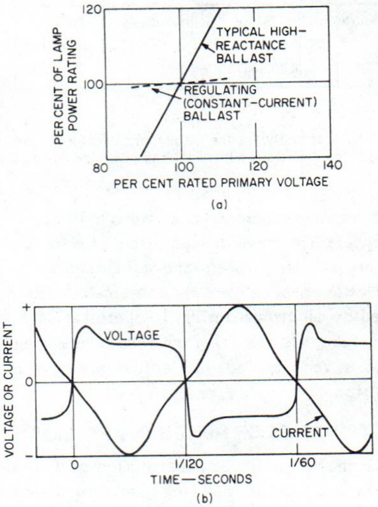


Fig.4 - Characteristics of conventional mercury-arc-lamp ballasts: (a) regulation characteristics; (b) voltage and current as a function of time.

SOLID-STATE BALLASTING CIRCUITS

The block diagram in Fig.5 shows the basic requirements of an electronic type of ballasting circuit for mercury-arc lamps. This type of ballast may be operated from either an ac or dc voltage source; the rectifier bridge, or course, is not required for dc source voltages. AC input voltages are first rectified, and the resultant dc voltage is then converted to the level required for

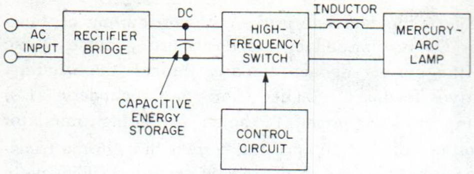


Fig.5 - Block diagram of an electronic ballasting system for mercury-arc lamps.

application to the mercury-arc lamp by some type of inverter or converter (solid-state switch and associated control circuit).

Efficient conversion of a voltage from one level to another level requires the use of an inductive component. If a size advantage is to be realized from the use of an electronic ballasting circuit, the frequency of the solid-state switch must be high enough so that the converter inductor is significantly smaller than a conventional 60-Hz ballasting reactor. A small inductor, however, cannot maintain the arc in a mercury-arc bulb as the ac source voltage swings through zero. If no other storage element were included in the electronic ballasting circuit, the arc would be extinguished; the mercury-arc lamp must then be allowed to cool sufficiently before a new arc can be produced. The electronic ballast, therefore, includes a capacitor for additional energy storage when the circuit is operated from an ac voltage source.

Fig.6 shows three prospective electronic ballasting circuits: a ringing-choke converter, a push-pull inverter, and a switching regulator. Table II summarizes the characteristics of each type. The important considerations in the selection of one circuit in preference to the other circuits are power-regulation capabilities, operating efficiency, small size, and requirements of the solid-state switching element.

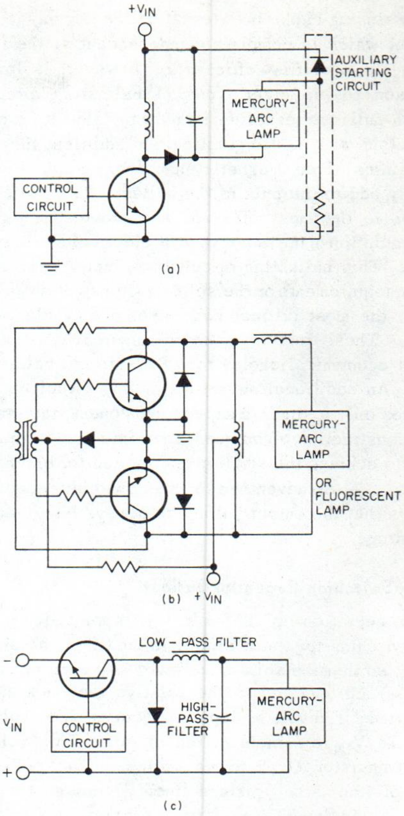


Fig.6 - Three basic circuit configurations that may be used in electronic ballasting systems: (a) ringing-choke converter; (b) push-pull inverter; (c) switching regulator.

TABLE II – CHARACTERISTICS OF VARIOUS ELECTRONIC BALLASTING CIRCUITS

						Switching Transistor		
CIRCUIT	V_{IN} - V_{OUT}	DC or AC OUT	REMARKS	REGULATION	APPROX. EFF.	No. of Devices	V_{CE}	I_C(peak)
Ringing Choke	Independent	DC	Complex Circuit (Open-load protection)	Excellent	70%	1	$V_{IN} + V_{OUT}$	$\sim$(4X) I_{OUT}
Push-Pull	Independent	AC	Three magnetic elements	Limited	80%	2	$2V_{IN}$	(4X) I_{OUT}
Switching Regulator*	$V_{IN} > V_{OUT}$	DC	Simple Circuit	Excellent	90%	1	V_{IN}	(2X) I_{OUT}

* The switching regulator offers the greatest efficiency and least stringent switching-transistor requirement.

The ringing-choke inverter offers the advantage of a dc output which is completely independent of the input voltage; its operating efficiency, however, is low in comparison to the other types of ballasting circuits. The push-pull inverter suffers from the fact that it provides an ac output with poor regulation. In addition, this circuit requires three magnetic components, which substantially add to the bulk of the ballast. The switching regulator is the most efficient and provides the best power regulation of the three types of electronic ballasting circuits. This ballasting circuit also imposes the least stringent requirements on the solid-stage power-switching element, the most critical component of any electronic ballast. These factors make the switching regulator the most economical choice for an electronic ballasting circuit. An additional advantage of this circuit is that it requires only a single magnetic component; integrated-circuit construction techniques, therefore can be readily applied to achieve the small sizes desired for ballasting elements. A disadvantage of the switching-regulator ballast is that the output voltage is always less than the input voltage.

120-Volt Switching-Regulator Ballast

For operation in 120-volt line applications, the basic switching-regulator circuit is modified, as shown in Fig.7, so that the solid-state switching element (transistor Q_1) is operated in the positive feedback mode. The rectified 120-volt ac input appears as a dc voltage across the V_{IN} terminals of the circuit. This voltage drives transistor Q_1 into saturation. The collector current of transistor Q_1 rises linearly through the primary (L_1) winding of transformer T_1 until the voltage drop across the current-sensing resistor R_2 increases above a predetermined threshold level. At this point, transistor Q_3 is turned on, and the collector current of this transistor, in turn, drives transistor Q_2 into conduction to create a virtual short between base and emitter of transistor Q_1. In this way, the drive input to transistor Q_1 is effectively removed. The inductive kick from the L_1 primary winding of transformer T_1 that results from the decrease in the collector current of transsistor Q_1 is clamped by the commutating diode D_3 so that the current decays linearly through the winding. Positive feedback coupled from the secondary (L_2) winding of transformer T_1 holds switching transistor Q_1 in the ''off'' state until the current through the transformer primary winding decreases to zero. The cycle is then repeated. Fig.8 shows the significant current and voltage waveshapes for the circuit. It is apparent from these waveshapes that switching losses occur only during turn-off.

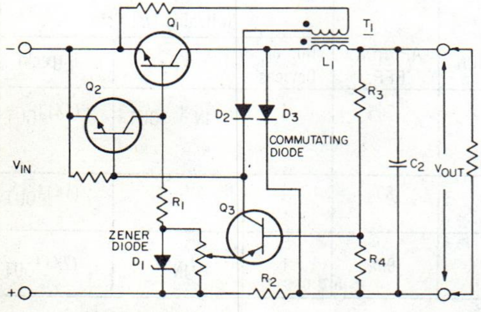


Fig.7 - 120-volt switching regulator.

The equations for the turn-on (t_{on}) and turn-off (t_{off}) times and the switching frequency (f) of the switching-regulator ballasting circuit can be derived from the following basic relationship for the voltage developed across an inductor:

$$E_L = L \frac{di}{dt} \tag{1}$$

During turn on, the voltage across the regulator inductor is essentially the algebraic difference between the input and output voltages (i.e., $E_L = V_{in} - V_{out}$). Because both of these voltages are constant, their difference results in a linearly increasing current through inductor L_1. The rate of change of the current (di/dt) is then the peak value to which the current rises divided by the turn-on period (i.e., $di/dt = I_{peak}/t_{on}$). For those conditions, Eq. (1) may be rewritten in the following form:

$$V_{in} - V_{out} = L_1 \frac{(I_{peak})}{t_{on}} \tag{2}$$

If this equation is solved for t_{on}, the following result is obtained:

$$t_{on} = \frac{L_1 (I_{peak})}{V_{in} - V_{out}} \tag{3}$$

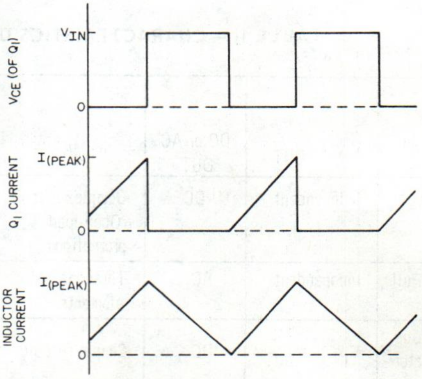


Fig.8 - Typical voltage and current waveforms for the switching regulator shown in Fig.7.

The equation for the turn-off time can be similarly derived. During this period, however, the voltage across inductor L_1 is essentially equal to the output voltage. The current decays linearly through the inductor so that the rate of change of current is constant over the turn-off period. When these conditions are imposed on Eq. (1), the following equation for the turn-off time can be derived:

$$t_{off} = \frac{L_1\,(I_{peak})}{V_{out}} \tag{4}$$

By use of Eqs. (3) and (4), the switching frequency of the switching-regulator ballast can be expressed in terms of the inductor L_1, the peak current, and the input and output voltages:

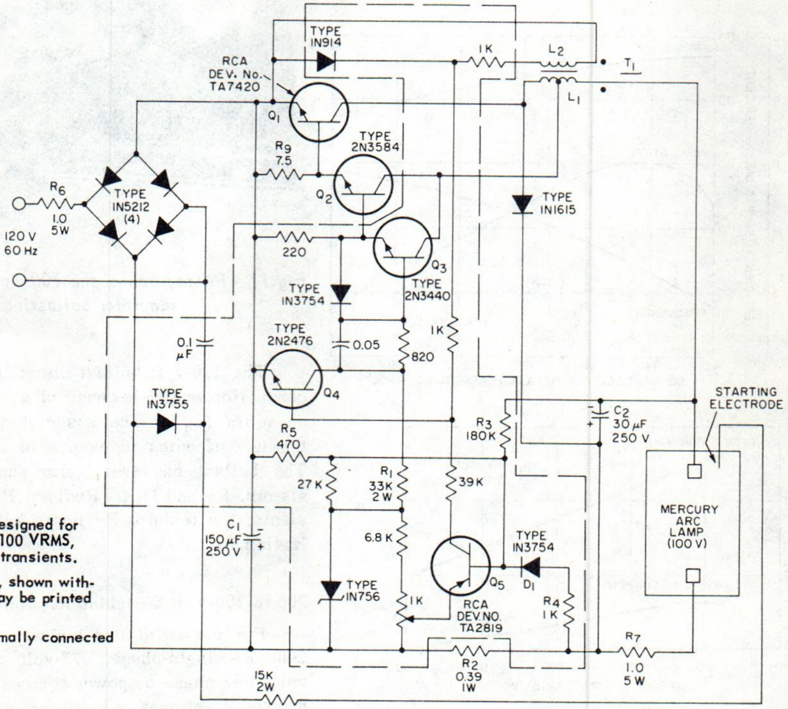
$$f = \frac{1}{t_{on} + t_{off}}$$

$$= \frac{V_{out} + (V_{in} - V_{out})}{L_1\,(I_{peak})\,(V_{in})} \tag{5}$$

The peak current and associated output voltage of the switching-regulator circuit can be varied by adjustment of potentiometer R_6. For any given setting of the potentiometer, however, these quantities are constant and are independent of the input voltage. Another factor of interest, which is apparent from Eq. (5), is that a change in power level (i.e., in V_{in} or I_{peak}) results in an inverse change in switching frequency.

Fig.9 shows a practical 100-watt switching-regulator ballasting circuit designed for 120-volt line applications in which the output voltage and current are both sampled to reduce bulb warm-up time. This circuit has a voltage-current characteristic very similar to that shown in Fig.2(b) for a conventional ballasting reactor.

The 120-volt ac input is rectified by a full-wave bridge rectifier. The dc output from the rectifier, is developed across filter capacitor C_1. Because the input drive to the emitter-base circuit of the switching transistor is applied through a resistance network, the relatively high supply voltage can lead to serious I^2R loss-



NOTES:
1. **This circuit is designed for operation above 100 VRMS, with 250 V peak transients.**
2. **Control circuitry, shown within dotted line, may be printed circuit.**
3. **Diode D_1 is thermally connected to transistor Q_5.**

Mercury arc lamp = 90-to-100-volt type with separate starting electrodes

L_1 = 120 turns of No.22 wire tapped 1 turn from collector

L_2 = 18 turns of No.34 wire

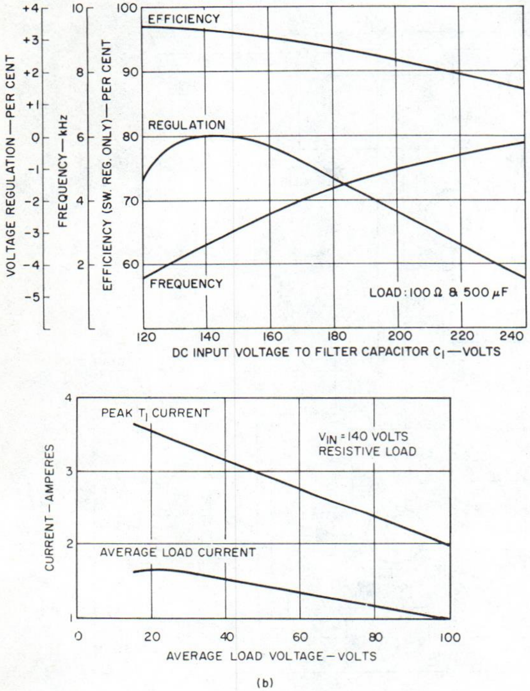
T_1 = Arnold AH 361 (or equiv.) with 0.036" gap (6.7:1 turns ratio)

Fig.9 - 100-watt, 120-volt ac switching-regulator ballasting circuit.

es unless the drive current is maintained at a very small value. This condition is made possible by use of two transistors Q_2 and Q_3 in a Darlington configuration to provide the current gain necessary to increase the low value of drive current to the level required to saturate the switching transistor.

Because the switching regulator is a "down converter," has limited filtering, and operates from relatively low line voltages, a special low-voltage (100-volt rather than the more common 135-volt) mercury-arc lamp is used with the 100-watt, 120-volt ballasting circuit. The low-voltage arc tube contains slightly less mercury than the higher-voltage type. High starting potentials are obtained by use of a half-wave voltage doubler, wired to a separate starting electrode (with a current-limiting resistor).

Performance data of the 100-watt switching regulator are shown in Fig.10. These data are shown as a function of the dc input voltage to filter capacitor C_1. The overall efficiency of the circuit, including the rectifier bridge and filter capacitor, is 87 per cent for a 120-volt ac input. The output is adjustable from 15 to 150 watts for operation of the circuit into a 100-ohm load impedance. The excellent regulation characteristics are achieved in part, by the action of resistor R_5, which offsets a rise in output voltage with a corresponding rise in input voltage. Fig.11 shows a photograph of the 100-watt, 120-volt switching-regulator ballasting circuit, together with a mercury-arc lamp.



(b)

Fig.10 - Performance characteristics of the 100-watt, 100-volt switching-regulator ballasting circuit: (a) voltage regulation, frequency response, and efficiency; (b) output characteristics.

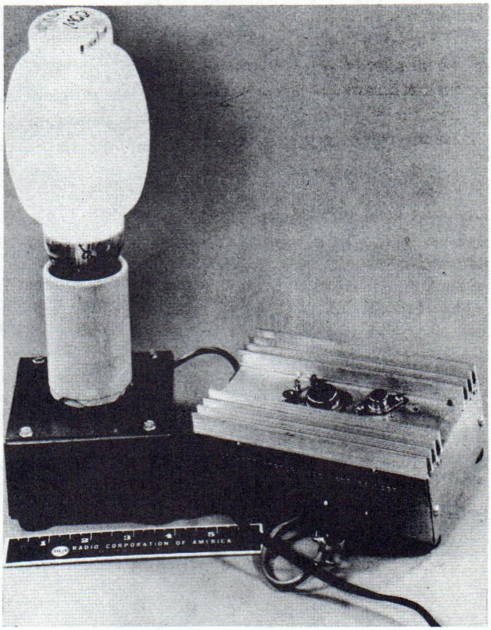


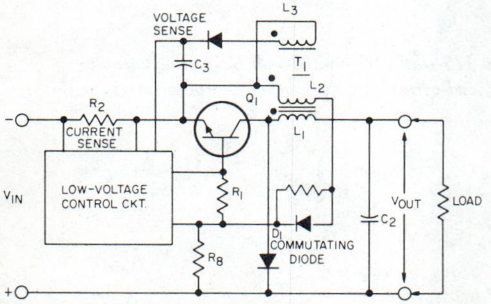
Fig.11 - Photograph of the 100-watt, 120-volt switching-regulator ballasting circuit.

The 120-volt ballast circuit has a relatively small conduction angle, because of a necessarily large filter capacitor (C_1). The associated surge currents make the use of bulbs in excess of 200 watts impractical. The ballast has two 1-ohm surge-current-limiting resistors, R_7 and R_{10}. Resistor R_{10} limits ac line transients; the resistor R_7 limits bulb current during ionization.

200-to-300-Volt Switching-Regulator Ballasts

For industrial and highway lighting installations, 240-volt single-phase, 277-volt single-phase, and 208-volt three-phase ac power sources are readily available. For these voltages, a sufficient differential between the arc-tube voltage and input voltage exists to permit the transistor switching element to be driven from a secondary winding on the inductor of a low-pass filter. Relatively high drive currents can then be obtained without high power losses.

Fig.12 shows the basic configuration for a switching regulator designed to operate from ac source voltages between 200 and 300 volts. Eqs. (1) through (5) and the waveshapes shown in Fig.8, given for the 120-volt switching-regulator ballasts, are also applicable to higher-voltage ballasts of the type shown in Fig.12. A unique feature of the higher-voltage circuits is that only the high-current switching transistor Q_1 is required to have a breakdown-voltage capability sufficient to withstand the full value of the dc input voltage including transients applied across the V_{IN} terminals. All the transistors in the control circuit are low-voltage, low-dissipation types. The design for the higher-voltage ballast also features built-in short-circuit protection.

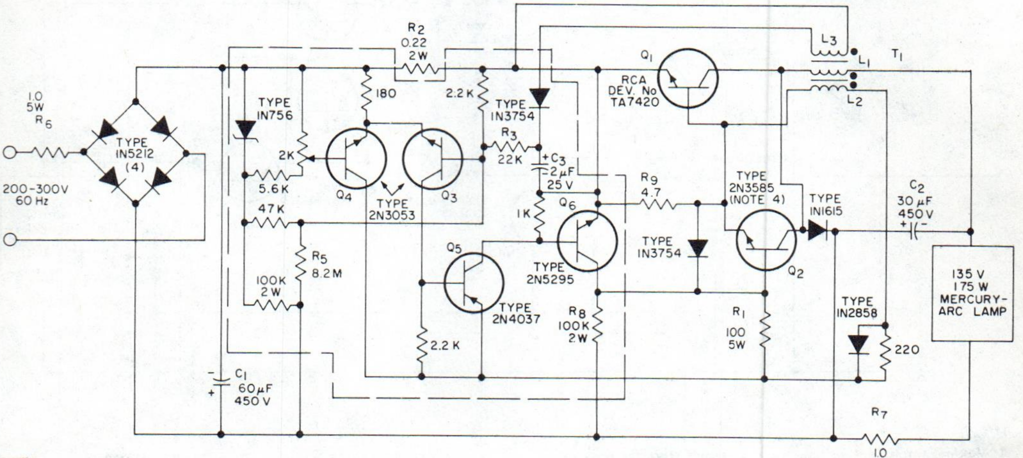


NOTE: This circuit needs only one high-voltage switching element.

Fig.12 - 200-to-300-volt ac switching regulator.

In the switching-regulator circuit shown in Fig.12, the dc voltage applied in the V_{IN} terminals drives a switching transistor (Q_1) that is slightly forward-biased by a small current (approximately 3 milliamperes) through a base-circuit resistor (R_8). Transistor Q_1 is immediately driven into saturation by the positive feedback from its collector circuit supplied by the L_2 secondary winding of transformer T_1. The L_2 secondary winding also supplies the drive power to the control circuit. The collector current of switching transistor Q_1 rises linearly through the L_1 primary winding of transformer T_1 until the voltage across the current-sensing resistor R_2 triggers the control circuit in shunt with the base-emitter junction of transistor Q_1. The transistor is then held cut off by the feedback voltage from the L_2 secondary winding of the transformer until the current through L_1 primary winding decays to zero. The inductive kickback that results from the decrease in current through L_1 is clamped by the commutating diode D_1 and, therefore, is the same as the output voltage on C_2. The L_3 winding of transformer T_1 then charges capacitor C_3 to a voltage proportional to the output voltage. During the next cycle, the control circuit samples a combination of the voltage across capacitor C_3 and the current through resistor R_2. In this way, an output characteristic similar to that of a conventional ballast, shown in Fig.2(b), is obtained.

The schematic diagrams and performance data for two practical ballasting circuits, designed for use with 175-watt and 400-watt memory-arc bulbs, that use the approach illustrated by the basic circuit configuration shown in Fig.12 are shown in Figs.13 and 14 and Figs.15



NOTES:
1. Maximum transient voltage = 450 V.
2. Control circuit shown within dotted line may be printed circuit.
3. Transistors Q_3 and Q_4 are thermally connected.
4. Transistor Q_2 is selected for a $V_{CER(sus)}$ at 200 ohms greater than 500 volts.

T_1 = 2 x Arnold AH-108 (or equiv.) with 0.054" air gap 17:1.7:1 turns ratio
L_1 = 120 turns of No.22 wire
L_2 = 12 turns of No.32 wire
L_3 = 7 turns of No.32 wire

Fig.13 - 175-watt, 200-to-300-volt switching-regulator ballasting circuit.

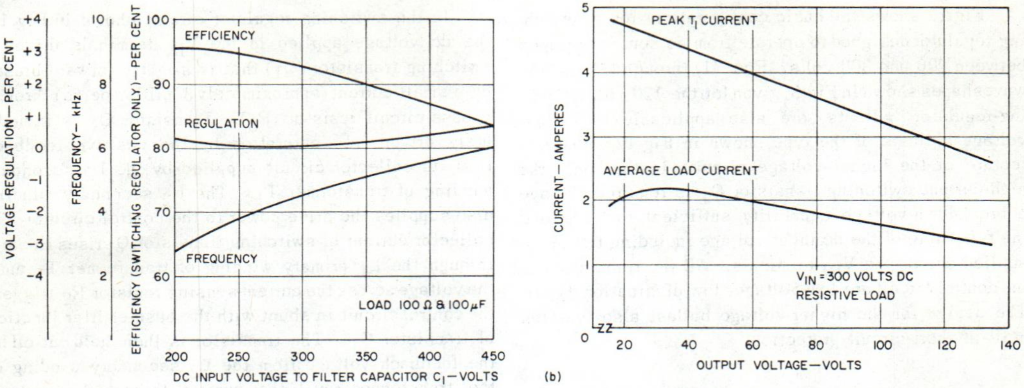
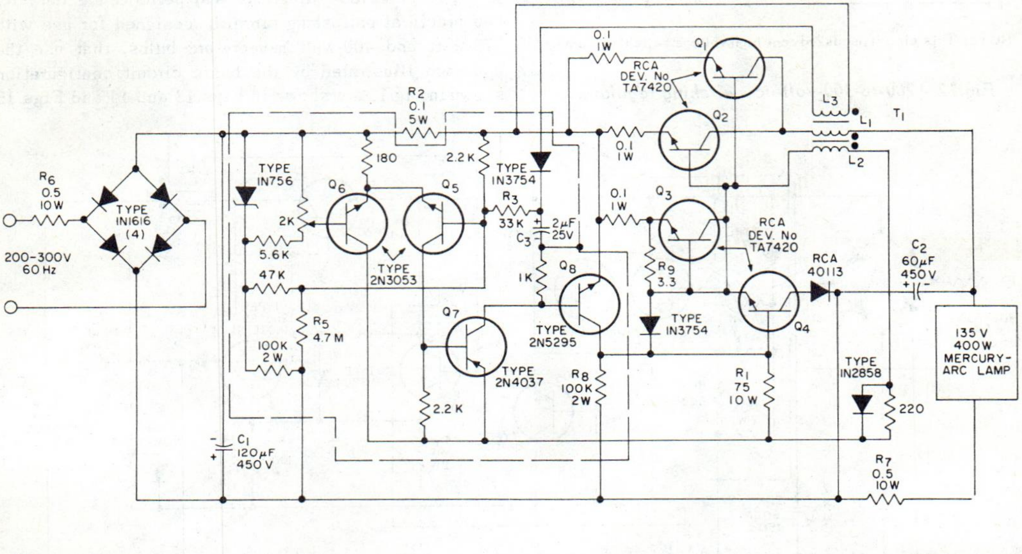


Fig.14 - Performance characteristics of the 175-watt, 200-to-300-volt ballasting circuit: (a) voltage regulation, frequency response, and efficiency; (b) output characteristics.



Notes:
1. Maximum transient voltage = 450 V.
2. Control circuit shown within dotted line may be printed circuit.
3. Transistors Q_1 through Q_4 are selected to have a $V_{CER(sus)}$ at 20 ohms greater than 500 volts.
4. Transistors Q_5 and Q_6 are thermally connected.

T_1 = Arnold AH-223 (or equiv.) with 0.125 inch air gap, 17:1.7:1 turns ratio
L_1 = 98T turns of No.18 wire
L_2 = 10T turns of No.32 wire
L_3 = 6T turns of No.32 wire

Fig.15 - 400 watt, 200-to-300 volt switching-regulator ballasting circuit.

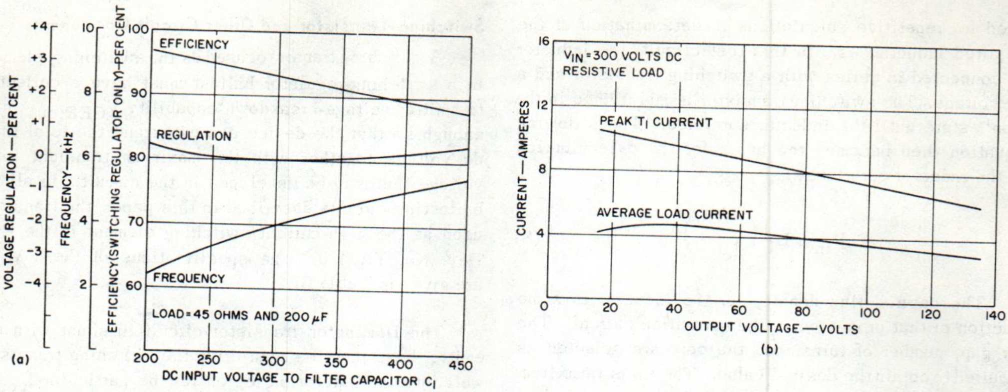


Fig.16 - Performance characteristics of the 400-watt, 200-to-300-volt switching-regulator ballasting circuit: (a) voltage regulation, frequency response, and efficiency; (b) output characteristics.

and 16, respectively. Performance data are shown as a function of the dc input voltage to filter capacitor C_1. Excellent regulation is obtained for dc input voltages from 200 to 450 volts. Fig.17 shows a photograph of the two ballasting circuits.

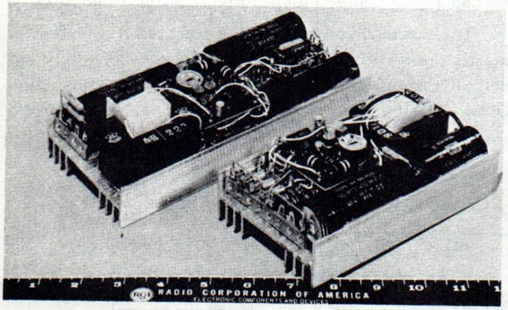


Fig.17 - Photograph of 175-watt and 400-watt 240-volt switching-regulator ballasts for mercury-arc lamps.

DESIGN PROCEDURE

The design of solid-state switching-regulator ballasts for mercury-arc lamps involves three critical operations: (1) selection of the mercury-arc lamp and the peak starting current, (2) selection of the reactor element, and (3) selection of the switching transistor and other circuit components.

Mercury-Arc Lamp and Peak Starting Current

The type of mercury-arc lamp used and the peak starting current that must be supplied to this lamp by the ballast circuit are dictated by the value of the ac source voltage, the amount of lamp power (P_L) required, and the warm-up time of the lamp. For operation from a 120-volt ac line at lamp power levels up to 200 watts, the special low-voltage (90-to-100-volt) type of mercury-arc lamp should be used. The peak starting current is then determined from the following relationship:

$$I_{peak} = 4\left(\frac{P_L}{100V}\right) \tag{6}$$

For operation from ac source voltages in the range of 200 to 300 volts, the more conventional 135-volt type of mercury-arc lamp is used. The peak starting current, for a specified bulb power rating P_L, is then determined as follows:

$$I_{peak} = 4\left(\frac{P_L}{135V}\right) \tag{7}$$

Switching-Regulator Reactor Element

The series inductor selected for the switching-regulator ballasting circuit should have a maximum core cross-sectional area and minimum air gap, consistent with the required inductance value, so that the minimum physical size is obtained. The circuit shown in Fig.18 permits simple di/dt measurements that eliminate the

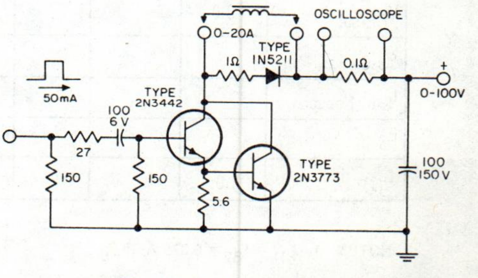


Fig.18 - Inductor tester.

need for repetitive calculations in determination of the required inductances. In this test circuit, the inductor is connected in series with a switching transistor and a dc voltage. The switching transistor is maintained in the "on" state until the inductor saturates. The following equation then becomes the basis for the determination of the inductor parameters:

$$V_{in} = L_1 \left(\frac{I_{sat}}{t_{on}}\right) \tag{8}$$

The desired flux density for the inductor is some fraction of that producted by the saturation current. The air gap, number of turns, and the core are selected as required to obtain the desired value. The turns ratio from the series inductor winding (primary) to the secondary windings is as indicated in the circuit schematics (Fig.9, 13, or 15) of the type of switching-regulator ballast being designed.

If an iron core is used for the inductor, the core laminations should be 4 mils thick (only a negligible increase in efficiency results from the use of thinner laminations). For stabilized operation and to avoid overheating of the inductor, the switching frequency of the ballasting circuit should be less than 5 kHz and the flux density in the inductor should be less than 6 kilogauss. For an inductor that uses a ferrite core, the flux density (determined for worst-case conditions) is usually 3 kilogauss, and the frequency is limited by only the transistor switching losses.

Switching Transistor and Other Circuit Components

A switching transistor used as the switching element in a switching-regulator ballast must have a collector-to-emitter voltage-breakdown capability $V_{CER(sus)}$ high enough so that the device can withstand the total input dc voltage together with the maximum transient input voltage that may be developed in the circuit. In all the ballasting circuits described in this paper, the transistor used as the high-current switching element is the RCA Dev. No. TA7420. The specifications of the TA7420 are given in Table III.

The Darlington transistor circuit in shunt with the emitter-base junction must drive the switching transistor well into the saturation region for the particular I_{peak}.

1. For the 120-volt ballast-circuit design,

   I_B (max) < 10 mA

2. For the 200-to-300-volt ballast-circuit design,

   I_B (max) < 300 mA

Approximately 20 per cent of the base drive to the switching transistor is diverted by resistor R_9 (in Figs.9, 13, and 15) to achieve rapid turn-off of the transistor.

The power dissipated by the transistor selected for use as the switching element should not exceed 10 per cent of the power rating (P_L) of the mercury-arc bulb. The transistor power dissipation (P_D) is calculated for

TABLE III – SPECIFICATIONS FOR THE RCA DEV. NO. TA7420 TRANSISTOR

Parameter	TEST CONDITIONS AT 25°C ± 3°C						Unit	Limit	
	I_C A	R_{BE} OHMS	V_{BE} V	V_{CE} V	I_B A	L μH		Min.	Max.
$V_{CER(sus)}$	0.2	50					V	375	
$V_{CEO(sus)}$	0.2						V	300	
I_B	0.5			5.0			A	0.005	
$V_{CE(sat)}$	3.0				0.375		V		1.0
$\theta_{J\text{-}C}$							°C/W		1.75
$I_{S/b}$ (1 second)				40			A	2.5	
$E_{S/b}$		20	-4			500	A	4.0	
$t_{f(1)}$	3.0			200	0.375		μS		0.5

NOTES: 1. $I_{B1} = I_{B2} = 0.375$ A; ($h_{FE} = 8$)

2. The RCA Dev. No. TA7420 is an epitaxial-overlay switching transistor in a JEDEC TO-3 case.

a hot, stabilized bulb ($I_{Cmax} = I_{STAB} = 2\,I_{avg}$) as follows:

P_D = saturation loss + turn-off loss

$$= \frac{t_{on}}{t_{on} + t_{off}} \int_{0}^{I_{STAB}} i\,R_{(sat)}\,di + \frac{f\,(STAB) V_{IN}\,t_f}{2}$$

$$\left(\frac{I_{STAB}\,f}{2}\right) \left[t_{on} \left(I_{STAB}\right) \left(R_{sat}\right) + V_{IN}\,t_f \right] \quad (8)$$

In Eq.8, $R_{(sat)}$ is the saturation resistance of the switching transistor, and t_f is its turn-off time for the particular circuit conditions. [It should be noted that the turn-off time is not directly related to the gain-bandwidth product (f_T).]

The total base drive resistance of the switching-regulator ballasting circuits can be estimated on the basis of the current and voltage relationships for peak-current conditions.

1. For the 120-volt design, the voltage drop across the total of the resistors in the base drive circuit is the dc input voltage less the voltage (8.2 volts) across the 1N756 Zener diode. The maximum value for the drive-circuit resistance I_{peak}, therefore, can be calculated by use of following equation:

$$R_{IN} = \frac{V_{IN\,(min)} - 8.2\ V}{I_{B(max)}}$$

$$= \frac{100}{I_{B(max)}} \quad (9)$$

   Eq.(9) indicates that the drive-circuit resistance for the 120-volt ballast design must be greater than 9000 ohms for a permissible $I_{B(max)}$ of 10 milliamperes.

2. For the 200-to-300-volt design, the total drive-circuit resistance is estimated as follows:

$$R_{in} = \frac{V_{in(min.)} - V_{out(min.)}\ \dfrac{L_2}{L_1} - 2\ V}{I_{B(max.)}} \quad (10)$$

   In this case, the drive-circuit resistance must be greater than 60 ohms for the 300 milliamperes of maximum permissible drive in the circuits presented.

The values of capacitors C_1 and C_2 and of resistors R_2, R_7, and R_{10} are determined on the basis of the type of circuit being designed and the power rating of the mercury-arc lamp with which this circuit is to be used. When the lamp power rating (P_L) differs from that shown in the circuit diagrams of Figs.12 and 14, the values of C_1, C_2, $1/R_2$, $1/R_7$, and $1/R_{10}$ should be increased or decreased in direct proportion to the change in the lamp power rating, i.e.,

$$\frac{C_1}{C_1'} = \frac{C_2}{C_2'} = \frac{R_2'}{R_2} = \frac{R_7'}{R_7} = \frac{R_{10}'}{R_{10}} = \frac{P_L}{P_L} \quad (11)$$

where the prime (') indicates the new circuit values.

The bridge-rectifier diodes and the commutation diode are selected on the basis of the maximum voltage and current requirements of the ballasting circuit.

The value of resistor R_3 is determined from the desired voltage-current slope of the ballast circuit.

$$VI_{(slope)} = - \frac{I_{bulb\ (hot)}}{V_{bulb\ (hot)}} \quad (12)$$

An increase in the warm-up time for a given bulb and ballasting circuit arrangement can be achieved by the use of a larger resistor R_3 in both the 120-volt and 200-to-300-volt designs. This larger resistor would result in a smaller voltage-current slope, as shown in Fig.19, and the collector current during starting (I_{PEAK}) would then be reduced.

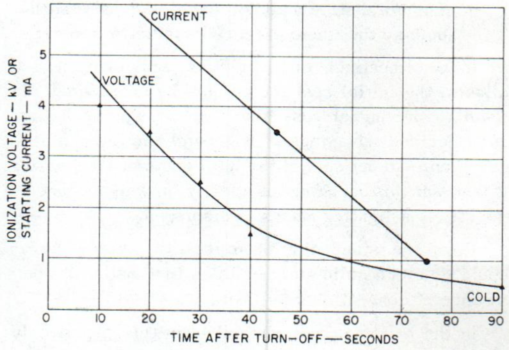


Fig.19 - Typical warm-up characteristics for a 100-watt mercury-arc lamp.

The value of R_5 is selected to provide the best voltage regulation.

ADVANTAGES OF SOLID-STATE MERCURY-ARC-LAMP BALLASTING

The circuit configuration and design procedure for the solid-state ballasts present several noted advantages over conventional ballasts.

1. Because no strobe effect is associated with the solid-state ballasts, it is possible to use long-life, efficient mercury-arc lamps in studios and

in similar critical lighting areas. In such applications, the low lighting cost and the advantage of more light with less heat are decisive factors in favor of mercury-arc lamps.

2. Solid-state ballasts provide unmatched power regulation for line voltage fluctuations.
3. The new ballasts offer the physical advantages of reduced weight and bulk in comparison to conventional ballasts. For example, the weight of a 400-watt conventional ballast is approximately 13 pounds, while the weight of an equivalent solid-state ballast is only 2.4 pounds. It is anticipated that the weight and bulk of solid-state ballasts will be further reduced by the use of hybrid circuit techniques and ultrasonic operating frequencies.
4. A solid-state photocell control is required to switch only milliwatts of power to actuate a solid-state ballast, rather than the kilowatts that would be required for a conventional ballast.
5. The circuits permit adjustment of 70 to 150 per cent of rated bulb wattage. Outside this range, the negative-impedance characteristics of the bulb cause the arc to be extinguished. However, one basic ballast circuit may be used for bulbs of various power ratings.
6. The solid-state ballast supplies dc power to the bulb so that there are no RFI radiation problems.

In a comparison of solid-state and conventional ballasts, the initial cost factor must be considered. In regard to the initial cost, the simple magnetic ballast has a decided advantage. In general, however, initial cost is only 10 per cent of the total costs of the lighting system, and this advantage is clearly outweighed when a less efficient lighting means is displaced.

From the standpoint of reliability, proper design should result in solid-state ballasts that match the performance of conventional ballasts.

In the ballast circuit described in this paper, only transistors were used. Thyristors (SCR's and triacs) are also suited for use in ballasting circuits for arc-discharge lighting systems, particularly at high power levels.

Significant future growth in mercury-arc lighting for both home and office should favor the transistor ballast at voltage and power levels below 120 volts and 100 watts.

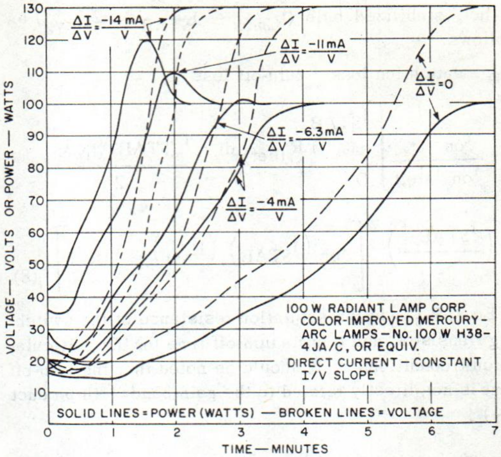


Fig.20 - Hot restart characteristics for a 100-watt mercury-arc lamp.

ADDITIONAL DEVELOPMENTS

A major disadvantage of mercury-arc lamps is the cooling-off period (approximately 5 minutes) required before a lamp previously in use can be restarted. Fig. 20 shows the measured hot restart characteristics of a 100-watt mercury-arc lamp. These curves were obtained by use of only the main electrodes of the quartz burner. This technique effectively halved the cooling time. Work is currently underway to solve the problem through the development of new circuits that permit instant hot restarts of mercury-arc lamps.

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