United States Patent [19]

Siedband et al.

[11] **3,766,391**

[45] **Oct. 16, 1973**

[54] **RMS CURRENT REGULATOR FOR AN X-RAY TUBE**

[75] Inventors: **Melvin P. Siedband; Jack L. James,** both of Baltimore, Md.

[73] Assignee: **CGR Medical Corporation,** Baltimore, Md.

[22] Filed: **Apr. 24, 1972**

[21] Appl. No.: **247,027**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 742,463, July 3, 1968, abandoned, Continuation of Ser. No. 115,060, Feb. 12, 1971, abandoned.

[52] **U.S. Cl.** **250/403,** 315/302

[51] **Int. Cl.** **H05g 1/32,** H05g 1/34

[58] **Field of Search** 250/97, 99, 102, 250/103; 315/291, 302

[56] **References Cited**

UNITED STATES PATENTS

2,494,218	1/1950	Weisglass	250/97
2,627,035	1/1953	Ball	250/97
2,810,838	10/1957	Clapp et al.	250/103

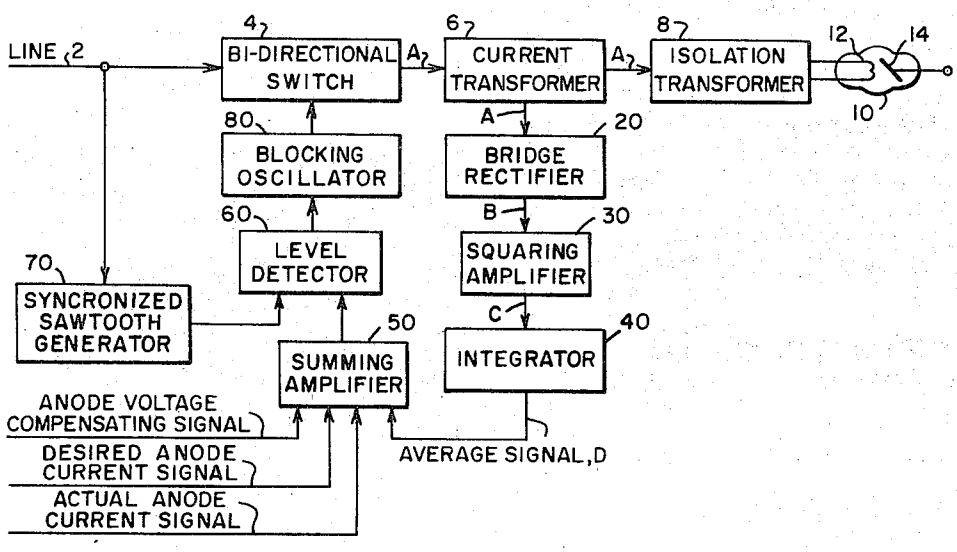
Primary Examiner—William F. Lindquist

Attorney—Rupert J. Brady

[57] **ABSTRACT**

A solid state RMS current regulator for controlling the amount of X-rays produced by an X-ray generator. The filament power to the X-ray generator is regulated by obtaining the average of the square of the instantaneous current through the filament of the X-ray generator. This indication is in perfect proportion to the square of the effective or RMS current and is directly related to the average power delivered to the filament. The sensed indication is compared with an X-ray generator operation reference signal for firing a semiconductor switch to control the RMS current through the filament.

15 Claims, 7 Drawing Figures



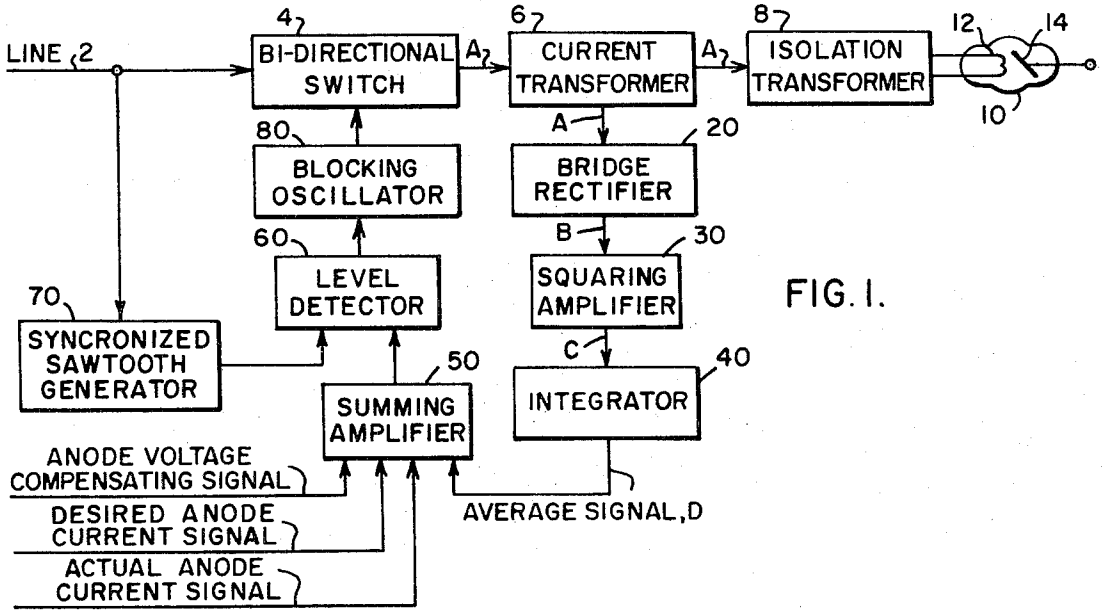


FIG. 1.

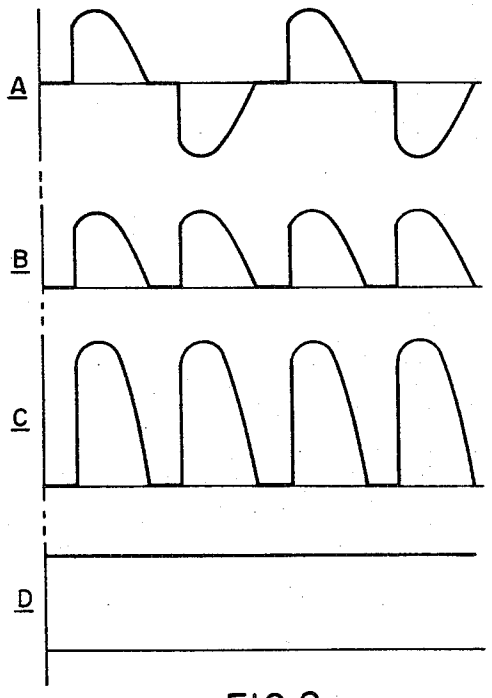


FIG. 2.

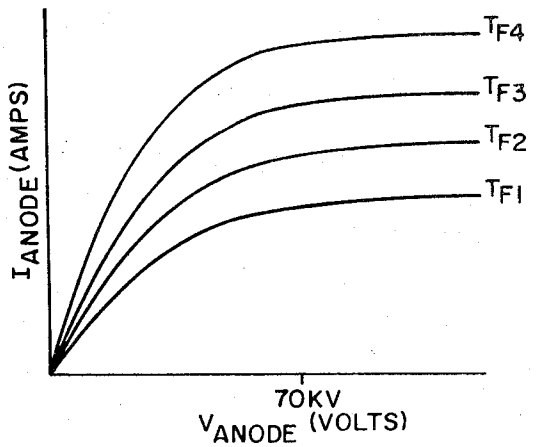


FIG. 3.

WITNESSES:

Bernard R. Giegueg

James T. Young

INVENTORS
Melvin P. Siedband &
Jack L. James.

BY Ernest P. Klipfel
ATTORNEY

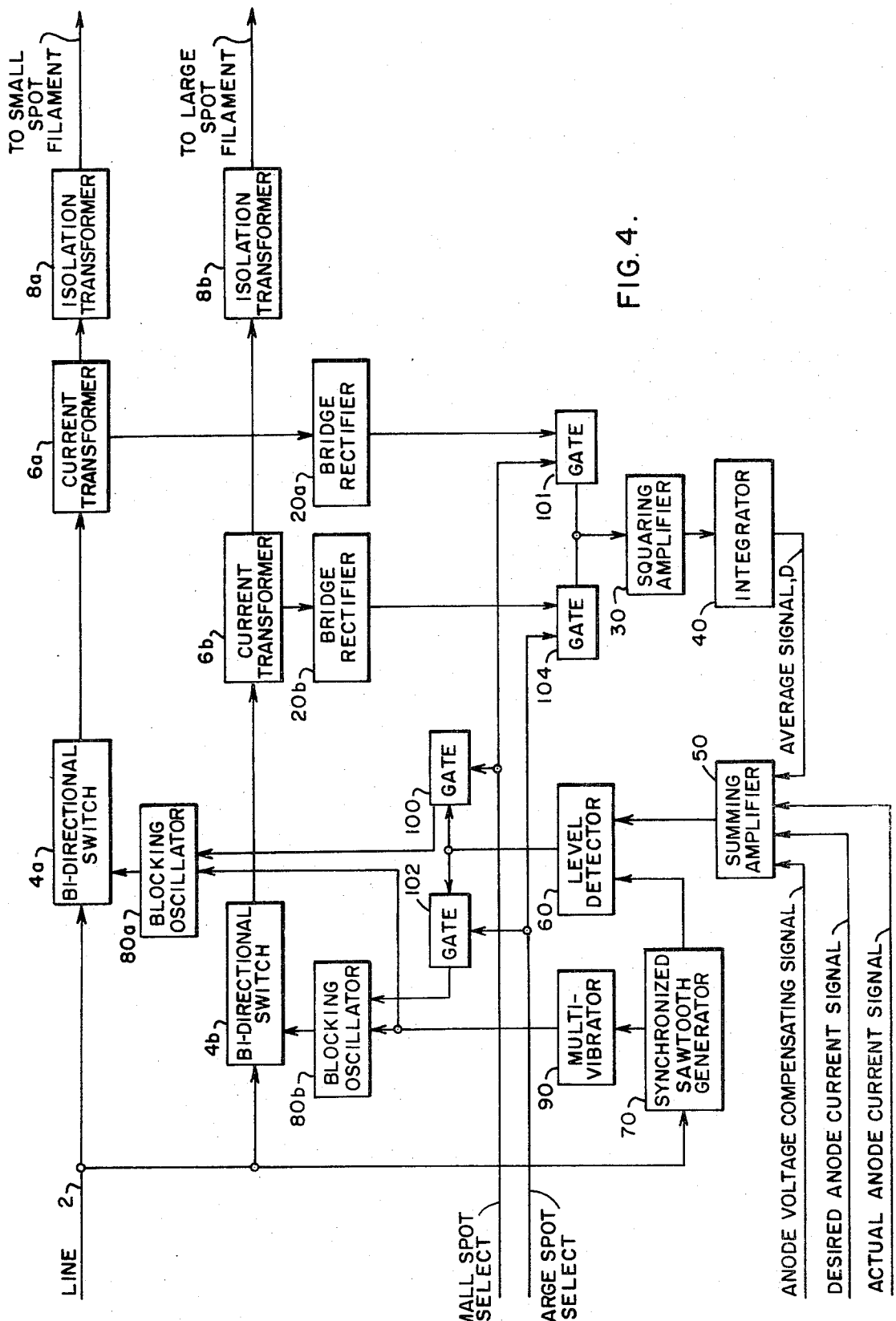
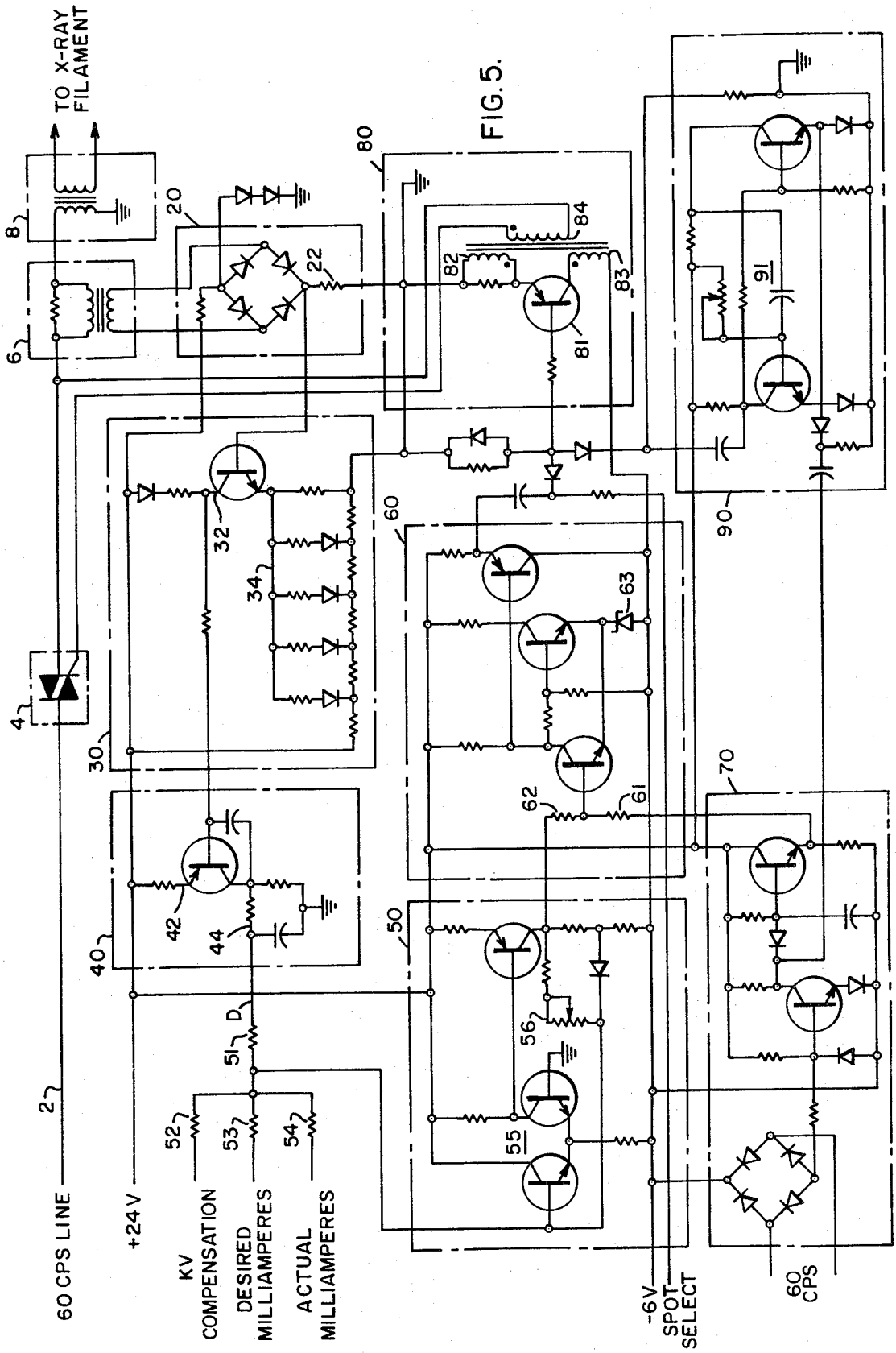

TO SMALL SPOT FILAMENT
TO LARGE SPOT FILAMENT
8a
ISOLATION TRANSFORMER
8b
ISOLATION TRANSFORMER
6a
CURRENT TRANSFORMER
6b
CURRENT TRANSFORMER
20a
BRIDGE RECTIFIER
20b
BRIDGE RECTIFIER
101
GATE
104
GATE
30
SQUARING AMPLIFIER
40
INTEGRATOR
AVERAGE SIGNAL, D
4a
BI-DIRECTIONAL SWITCH
80a
BLOCKING OSCILLATOR
100
GATE
102
GATE
50
SUMMING AMPLIFIER
60
LEVEL DETECTOR
4b
BI-DIRECTIONAL SWITCH
80b
BLOCKING OSCILLATOR
90
MULTI-VIBRATOR
70
SYNCHRONIZED SAWTOOTH GENERATOR
LINE
2
SMALL SPOT SELECT
LARGE SPOT SELECT
ANODE VOLTAGE COMPENSATING SIGNAL
DESIRED ANODE CURRENT SIGNAL
ACTUAL ANODE CURRENT SIGNAL

FIG. 4.

FIG. 5.


TO X-RAY FILAMENT
60 CPS LINE
+24 V
KV COMPENSATION
DESIRED MILLIAMPERES
ACTUAL MILLIAMPERES
-6V SPOT SELECT
60 CPS

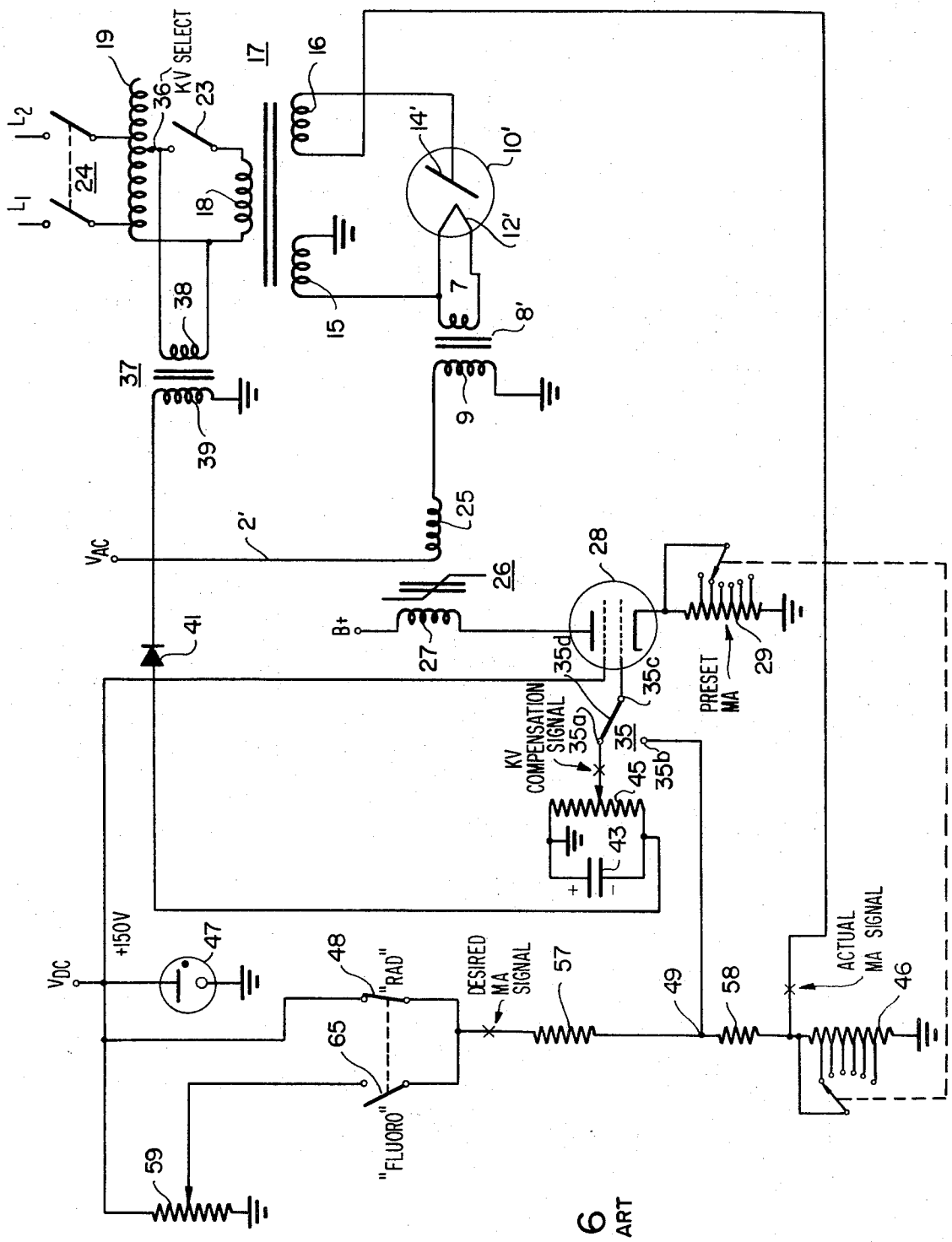


FIG. 6
PRIOR ART

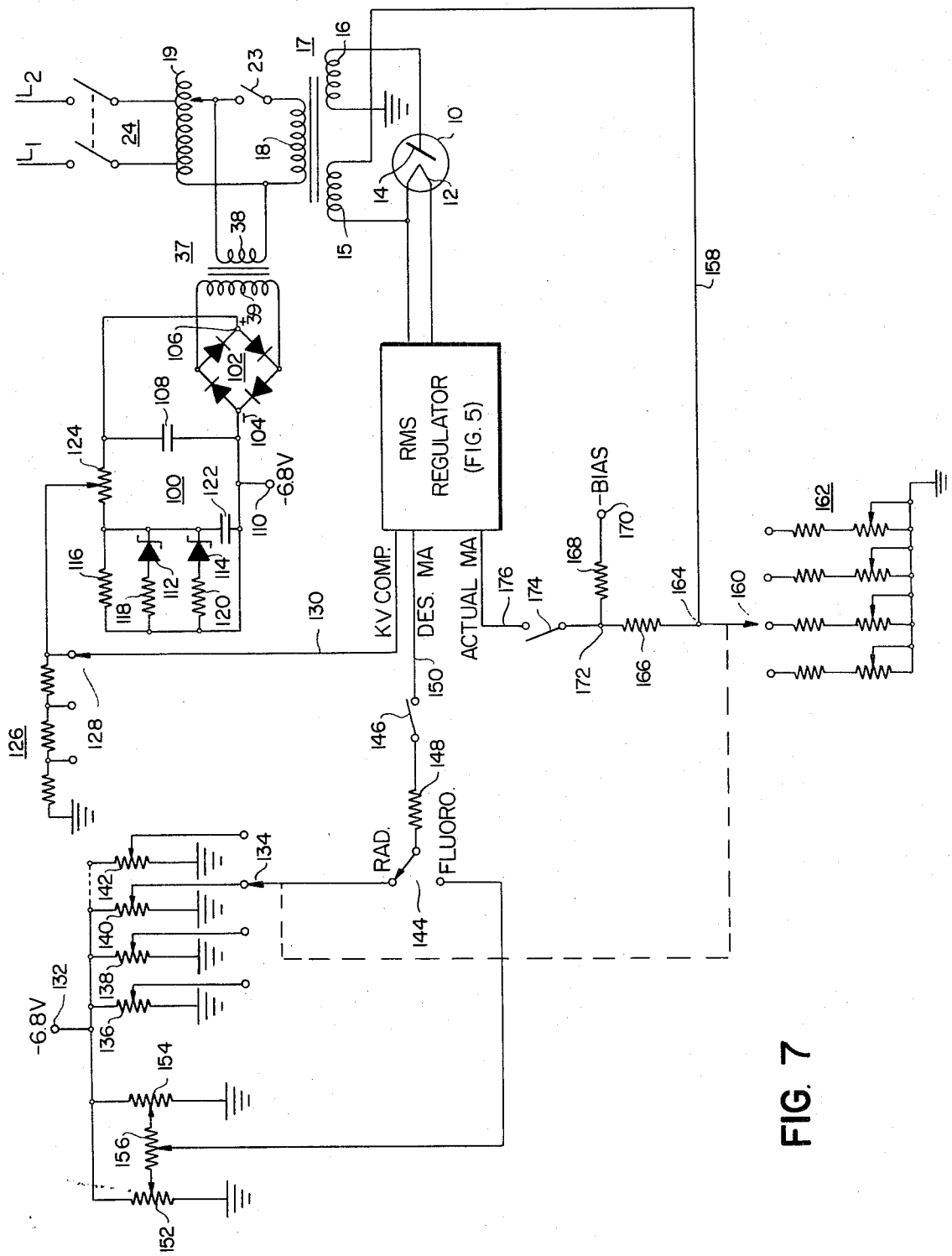

L2
L1
24
19
23
17
16
18
10
14
12
15
37
38
39
106
102
104
108
124
100
122
110
-6.8V
116
112
114
118
120
130
RMS REGULATOR (FIG. 5)
KV COMP.
DES. MA
ACTUAL MA
BIAS
168
170
176
174
172
166
164
160
162
158
126
128
146
148
150
RAD.
FLUORO.
144
134
142
140
138
136
132
-6.8V
154
156
152

FIG. 7

RMS CURRENT REGULATOR FOR AN X-RAY TUBE

CROSS REFERENCE TO RELATED APPLICATIONS 3, 1968,

This application is a continuation-in-part application of a parent application Ser. No. 742,463, filed July 3,1968, which was abandoned in favor of a streamlined continuation Ser. No. 115,060, filed Feb. 12, 1971, also now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to RMS current regulators and more particularly relates to an RMS current regulator for controlling the anode current of an X-ray generator tube.

2. Description of the Prior Art:

Present apparatus and methods of filament control of an X-ray generator tube are relatively expensive and slow to respond. The constant voltage line regulators and the need for filament load resistors result in massive, heat generating, transformer coupled circuitry which require dissipation of large amounts of power for proper control of anode current.

Other prior art devices failed to respond quickly enough since it takes time to heat and cool the filament, in an inexpensive manner because of circuit complexity, and did not have incremental control to add to the output a current for certain special purposes as would be required in an X-ray control.

An object of the present invention is to provide an RMS current regulator having a time of response which is considerably quicker than heretofore available.

Another object of the present invention is to provide an RMS current regulator capable of allowing incremental control, by increasing or decreasing the output as required for reasons other than power line stabilization.

Another object of the present invention is to provide an RMS current regulator which is less expensive, more compact, and lighter than any regulator heretofore available.

SUMMARY OF THE INVENTION

In order to control the amount of X-rays produced, the filament power to the X-ray generator is regulated. The anode current of the X-ray generator tube is determined by the temperature limited emission of the filament.

Briefly, the present invention accomplishes the above cited objects as well as accomplishing other objects and advantages by providing means for sensing the instantaneous current through the filament of an X-ray generating tube and obtaining the average of the square of the instantaneous current and algebraically summing it with selected reference signal values for obtaining an error signal which is used to regulate the power fed to the filament to a degree heretofore unavailable.

When desired, the choice of either fine or coarse focal spots within the tube as a function of the demands of the system is provided by regulating the RMS current to either filament within the same X-ray generating tube.

BRIEF DESCRIPTION OF THE DRAWINGS

Further objects and advantages of the present invention will be readily apparent from the following detailed description taken in conjunction with the drawings in which:

FIG. 1 is a schematic block diagram of an illustrative embodiment of the present invention;

FIG. 2 is a graphical representation of the waveforms which occur at selected points in the illustrative embodiment of FIG. 1;

FIG. 3 is a graphical representation of characteristic operating curves utilized in the control of X-ray emission from an X-ray generator tube;

FIG. 4 is a schematic block diagram of another illustrative embodiment of the present invention;

FIG. 5 is an electrical schematic diagram capable of use in either of the illustrative embodiments of FIGS. 1 and 4;

FIG. 6 is an electrical schematic diagram of prior art circuitry utilized for regulating filament current of an X-ray generator tube; and

FIG. 7 is an electric schematic diagram of the circuitry providing three selected reference signals for utilization by the present invention.

The anode current of an X-ray generator tube is determined by the temperature limited emission of the filament. In order then to control the amount of X-rays produced, the filament power to the X-ray generator tube is regulated. The regulator must maintain proper filament temperature with variations in line and anode voltages. A starting point filament temperature is provided to reduce the time required to bring the filament temperature up to the desired operating point at the time of the input command signal. A feedback loop is also provided for correction of filament temperature if actual anode current is different than the desired anode current. The regulator provides these functions for either fine or coarse focal spot within the tube, depending on the system demand.

Referring to FIG. 1, current drawn from a power line 2 is controlled by a semiconductor switching device 4 connected in series circuit combination with a current transformer 6 and an X-ray filament isolation transformer 8 to control the emission of X-rays from an X-ray generator tube 10. In this illustrative embodiment only one filament 12 is being controlled. Current through the anode 14 is determined by the temperature limited emission of the filament 12. The filament power to the X-ray generator tube 10 is regulated in order to control the amount of X-rays produced.

It is to be understood that the semiconductor switch may be of any suitable type which allows current therethough as determined by its firing angle. For example, a bidirectional semiconductor switch such as a Triac or a single SCR switch in a diode bridge or two SCR oppositely poled and parallely connected, are devices which may be advantageously used for the semiconductor switching device 4. Of course, any switch having the operating characteristics previously described may be utilized.

Since the instantaneous power delivered to the filament 12 carrying an instantaneous current, i, is i^2 times the resistance of filament 12, it is evident that the average power delivered is equal to the average value of the instantaneous current i^2 times the resistance. The effective or root mean square value of current is defined to be the square root of the average of the square of the instantaneous current, i. Thus, the average power is also equal to the square of the effective or root mean

square value of the current through the filament **12** times the resistance of the filament **12.** Since it is the RMS current through the filament **12** which is of interset in determing the average power to the filament **12** and hence its temperature, the present invention regulates the RMS current.

More particularly, the filament current is sensed by the current transformer **6** and fed to a bridge rectifier **20.** A rectified signal B is squared by the amplifier **30** and averaged by an integrator **40.**

The resultant waveforms are as illustrated in FIG. **2.** It can be seen that the average of the squared signal C which is shown as waveform D of FIG. **2** is directly related to the square of the RMS value of current through the filament **12.** The average signal (waveform D) is compared to i.e. algebraically summed, wth at least one, but preferably a plurality of reference signals (FIG. **1**) and a sawtooth signal in circuitry including a summing amplifier **50,** a level detector **60,** a synchronized sawtooth generator **70** and a blocking oscillator **80** for firing the bidirectional switch **4** at an earlier angle if the current A to the filament **12** is to be increased or at a later angle if the filament current A is to be decreased.

For a clearer understanding of how the reference signals shown in FIG. **1** are selected, attention is now directed to FIG. **3.** FIG. **3** illustrates the anode current in the anode **14** as a function of anode voltage for various temperatures of the filament **12.** It is to be noted that the anode current increases as the filament temperature increases. Once the knee of any operating temperature curve is exceeded the anod current increases relatively little with additional anode voltage. The anode current increases sufficiently, however, with anode voltage so that one of the reference signal inputs to the summing amplifier can advantageously be an "anode voltage compensating signal." The second reference signal input to the summing amplifier **50** comprises an initial setting of the "desired anode current" for a particular operating mode and the third corresponds to the "actual anode current" flowing in the tube **10.** These three reference signals and the average signal are summed in a manner to be more fully described subsequently, in the summing amplifier **50** which operates to provide an error signal output for effecting "null-seeking" servo loop type control of filament temperatures with variations in anode current.

The level detector **60** combines the error signal output from the summing amplifier **50** with a sawtooth waveform from the generator **70** to provide an enabling signal to the blocking oscillator **80.** The level detector **60** will enable the blocking oscillator **80** when the further instantaneous sum of the sawtooth waveform and the error signal output from the summing amplifier **50** exceeds a predetermined level (substantially 0 volts). The sawtooth waveform from the generator **70** is synchronized with the power line **2** to provide a 120 cycle sawtooth signal. Of course, the output from the summing amplifier **50** will determine when the 120 cycle sawtooth waveform exceeds the predetermined level set in the level detector **60.** Since the frequency of the sawtooth waveform is twice the line frequency, the semiconductor switching device **4** will be fired on each half cycle to allow current in both directions through the switch **4.** Thus, if any of the inputs to the summing amplifier decreases, the output increases which trips the level detector **60** earlier. This action results in an earlier firing angle of the switch **4** which increases the current to the tube filament **12.**

It is to be understood that where desired, the sawtooth waveform can be included as another reference input signal to a summing amplifier **50,** the insertion of the sawtooth as illustrated is merely a matter of design choice. In either event, the phase angle firing of the switch **4** is related to the algebraic sum of the input signals to the comparing circuit i.e. the summing amplifier **50.** When the algebraic sum of the average signal D, the anode voltage compensating signal, the desired anode current signal and the actual anode current signal are substantially zero, the switching point of the level detector **60** will be solely determined by the preset sawtooth waveform.

Circuitry for controlling two filaments of the X-ray generator tube **10** is illustrated in FIG. **4.** Each filament has its own semiconductor switch and current sensing and like reference characters have been assigned to those items which are similar to FIG. **1,** but with *a* and *b* identifying each circuit. Current to the first filament a is controlled by the semiconductor switch **4***a* connected in series circuit combination with a current transformer **6***a* and isolation transformer **8***a*. Similarly, current to the second filament b is controlled by a semiconductor switch **4***b* in series circuit combination with a current transformer **6***b* and isolation transformer **8***b*. Each filament has associated therewith a bridge rectifier **20***a* and **20***b* respectively.

When a small focal spot within the X-ray tube is desired, the filament a is selected, for example, by a small spot select signal which enables a gate **100** for the phase angle firing of the switch **4***a* and enables the gate **101** to allow the signal representing filament current from the bridge rectifier **20***a* to be squared by the squaring amplifier **30.**

Should a large focal spot be desired within the X-ray tube then a large spot select signal would instead enable a gate **102** to the semiconductor switch 4b and enable the gate **104** to allow the signal representing the filament current through filament b to the squaring amplifier **30.**

Either average signal D will be compared in the same manner as previously described for firing the particular semiconductor switch which is enabled.

The principal difference in the illustrative embodiment of FIG. **4** from that of FIG. **1** is that a multivibrator **90** is used to provide a delayed pulse to the two blocking oscillators **80***a* and **80***b* such that if the level detector **60** does not feed the blocking oscillator in time, the delayed pulse will, and by this means provide a certain minimum or idling current to the unused X-ray generator tube filament. The idling current maintains the temperature of the unused filament just below that point where anode current would be provided. This method speeds up the operation of the tube when that filament is selected.

An electrical schematic diagram of the illustrative embodiment is provided in FIG. **5.** The circuitry shown therein is capable of operation for a single X-ray generator filament and additionally illustrates the multivibrator **90** to encompass the operation of the illustrative embodiment of FIG. **4.**

The semiconductor switch **4** is illustrated as a bidirectional switch or Triac controlling current in either direction. The current transformer **6** senses the instantaneous current to the filament. The sense signal is rec-

tified by the bridge rectifier 20 with the voltage across the resistor 22 providing a signal to the squaring amplifier 30. An amplifier stage 32 and network 34 approximates the square of the voltage appearing across the resistor 22. The integrator 40 obtains the average of the squared signal in two stages 42 and 44. The average signal D is provided across a summing resistor 51. The previously mentioned desired reference input signals comprising the anode voltage compensation signal, hereinafter referred to as the KV compensation signal, the desired anode current or MA, and the actual MA are provided across summing resistors 52, 53 and 54, respectively. An operational amplifier 55, with its feedback resistor path 56 within the summing amplifier 50, provides an output to the level detector 60. The sawtooth generator 70 provides the sawtooth waveform across summing resistor 61. The output from the summing amplifier 50 is provided to the level detector 60 across the summing resistor 62. When the sum of the signals appearing across resistors 61 and 62 exceeds a predetermined level as determined by a Zener diode 63, the level detector 60 will provide a signal to the blocking oscillator 80. The transistor switch 81 provides a firing angle signal to the Triac 4 by conduction in windings 82 and 83 through winding 84. The location of the dots in relation to windings 82, 83 and 84 indicates the polarity of these windings to provide positive feedback to transistor switch 81 and the output pulse is applied to the Triac 4 during each half cycle of current to the filament from the power line 2.

A multivibrator 90 will also gate the switching transistor 81 at a time chosen by the constants within the interconnecting elements of a flip-flop 91. The output from the multivibrator 90 is selected to occur subsequent to the usual signal from the level detector 60 so that the arrangement whereby at least two X-ray generator filaments are being regulated, the delay pulse from the multivibrator 90 will provide a certain minimum current to the unused filament.

The three reference input signals comprising the anode or KV compensating signal, the desired anode current signal, and the actual anode current signal are well known to those skilled in the art, having been generated and utilized in prior art X-ray filament current regulators. An illustrative example is shown in FIG. 6. The schematic shown in FIG. 6 is taken from the overall assembly schematic drawing number 812C245 and sub-assembly schematic drawing number 618J480. These appear in Westinghouse Service Manual IHB 211, dated April, 1967. This circuit, moreover, corresponds to a portion of the filament current regulator circuit incorporated in a Westinghouse X-ray apparatus referred to as the "Denver" model, style 621B300G02 which has been in public use since June of 1967.

For an understanding of how these signals are developed and utilized, reference is now made to FIG. 6 wherein an X-ray generator tube 10' is shown coupled by means of its filament 12' and its anode 14' across the secondary windings 15 and 16 of a high voltage transformer 17 which has its primary winding 18 coupled to a variable KV selecte auto-transformer 19 through an X-ray exposure switch or relay contacts 23 which is closed when an X-ray exposure is desired. The auto-transformer 19, moreover, is connected to the power lines L_1 and L_2 through a double pole power "on-off" switch 24.

A filament isolation transformer 8' has its secondary winding 7 coupled across the filament 12' while the primary winding 9 is coupled to the AC power line 2' through the secondary winding 25 of a saturable core transformer 26 whose primary winding 27 is coupled between a B+ power supply potential and the plate electrode of a control vacuum tube 28.

The purpose of the control tube 28 is to vary the saturation of the core of the transformer 26 in accordance with the grid input signal which in turn varies the impedance of the secondary winding 25 and thus vary the amount of filament supply voltage applied to the primary winding 9 of the filament isolation transformer 8'. This voltage produces a filament current whereupon the filament temperature determines the anode current of the X-ray generator tube 10'.

An initial or pre-set value of X-ray tube anode current is initially selected by means of varying a rheostat 29 coupled between the cathode electrode and ground of the control tube 28. The value of resistance in combination with the voltage applied to the grid of the control tube 28 establishes an anode current therein which tends to effect a "pre-set" X-ray tube anode current when switch 23 is closed and the high voltage is applied across the anode 14 and cathode 12'.

A set of switch or relay contacts 35 which includes the contacts 35_a, 35_b and 35_c interconnected through a wiper 35_d are selectively connected to the grid electrode of the control tube 28. FIG. 6 as shown discloses wiper 35_d connecting contacts 35_a and 35_c whereby a KV compensation signal is applied to the grid of the control tube 28 during a pre-exposure time i.e. when switch 23 is open as shown in order to compensate for the so-called "space charge" effect which is well known to those skilled in the art. It is that effect which is inherent in presently known X-ray tubes that necessities increasing the X-ray tube filament temperature by increasing the filament current in order to maintain a constant anode current as the high voltage across the tube is reduced such as by moving the tap 36 of the auto-transformer 19. In the instant prior art apparatus, this signal is developed by means of a transformer 37 having its primary winding 38 coupled across the movable tap 36 and the lower end of the auto-transformer 19. The secondary winding 39 developes an AC signal which is half-wave rectified by means of a semiconductor diode 41. The unidirectional current from the diode 41 charges a capacitor 43 across which is coupled a potentiometer 45. By proper setting of the potentiometer the desired KV compensation signal is applied to the control tube grid prior to the X-ray exposure. This is particularly important where the circuitry utilized a preheated X-ray tube filament such as shown in FIG. 6.

When an X-ray exposure is desired, switch or relay contacts 23 is closed and switch 35 is simultaneously operated whereupon contacts 35_b and 35_c are interconnected through the wiper 35_d and the high voltage is applied across the X-ray generator tube 10'. During the X-ray generation time, the KV compensation signal is removed and a grid voltage is applied thereto which results from a comparison of the actual X-ray tube anode current and the desired anode current. A signal voltage corresponding to the actual anode current of the X-ray generator tube 10' is developed across a rheostat 46 which is commonly referred to as the "drop wire" resistance which has one end coupled to ground while the

other end is returned to one side of the high voltage secondary winding **16** which is connected to the anode **14'**. The rheostat **29** and **46** are ganged together and thus provide simultaneously selectable resistance values. This is particularly significant in the radiography or simply "RAD" operating mode where the actual anode current signal voltage is compared against a fixed reference signal voltage which corresponds to a desired X-ray tube anode current. This fixed referrence is developed by means of a voltage regulator tube **47** which is coupled to a DC voltage source and is adapted to provide +150 volts of DC voltage thereacross. This fixed voltage is applied through switch or relay contacts **48** which are closed in the "RAD" mode and is applied to a summing point **49** through a fixed resistor **57.** The voltage across the rheostat **46** which corresponds to the actual X-ray tube anode current signal is applied to the summing point through the fixed resistor **58.** The summing point **49** compares the desired X-ray tube anode current signal voltage (+150 volts) with the actual X-ray tube anode current signal and a difference or error voltage is applied to the grid of the voltage regulator tube **28** to cause the actual X-ray tube anode current signal to become substantially equal to −150 volts. If there is a difference between the desired and actual anode current signal voltages at the summing point **49,** the polarity of the difference voltage therebetween applied to the grid of the control tube **28** will be such that it will drive the saturable reactor **26** in the proper direction to cause the anode current of the X-ray generator tube **10'** to change until the desired and actual current signal voltages are equal at the summing point **49.**

In the fluoroscopy or "FLUORO" mode, a variable reference is required and is derived from a potentiometer **59** coupled across the voltage regulator tube **47.** The slider of the potentiometer **56** is coupled to switch or relay contacts **65** which are ganged with the contacts **48** which are closed in the "fluoro" mode to apply a predetermined lesser fixed value of DC signal to the fixed resistor **57** while the other contacts **48** are opened; however, the operation of the voltage comparison and the closed loop current control is the same in both instances. The only difference is that in the "RAD" mode the rheostat **46** is selectively varied while in the "FLUORO" mode, the value of the rheostat **46** is maintained fixed while the potentiometer **59** is varied. It should be pointed out that the relative magnitude of the KV compensating signal as compared to the desired anode current signal and the actual anode current signal is much less such that when desirable it may be continuously applied even during exposure time although its primary function is for pre-exposure connection of the filament current.

With the foregoing in mind, the present invention derives and utilizes the three reference signal inputs corresponding to the KV compensation signal, the desired anode current, and the actual anode current in a manner similar to that disclosed with respect to the prior art circuitry shown in FIG. **6,** but modified according to the circuit shown in FIG. **7** in order to be compatible with the circuitry shown in FIG. **5.**

Referring now to FIG. **7,** attention is first directed to the means for developing the anode voltage (KV) compensation signal. This circuitry is designated generally by reference numeral **100** and includes, inter alia, a full wave diode bridge rectifier **102** coupled across the secondary winding **39** of the transformer **37.** Transformer **37** is connected to the auto-transformer **19** in the same manner as described with respect to prior art circuitry in FIG. **6.** The negative output terminal of the bridge rectifier **102** is designated by reference numeral **104** while the positive output terminal is designated by reference numeral **106.** A filter capacitor **108** is coupled across terminals **104** and **106** and a negative bias (−6.8 volts) is coupled to the negative terminal **104** by means of terminal **110.** A non-linear network consisting of Zener diodes **112, 114,** resistor **116, 118, 120,** capacitor **122** and output potentiometer **124** is coupled across the capacitor **108** and rectifier output terminals **104** and **106.** The positive potentiometer at the slider of potentiometer **124** is fed to a resistor voltage divider network **126** whose voltages thereacross are selectively tapped by means of the switch **128.** Whereas the potentiometer **124** provides a rough setting, the switch **128** provides a fine selection of a positive potential which appear on circuit lead **130** and which is coupled to summing resistor **52** in FIG. **5.**

At low KV values, Zener diodes **112** and **114** are below their breakover or threshold voltage. However, as KV is increased, Zener diode **114** conducts first so that its resistor **120** is effectively in parallel with resistor **116.** This attenuates the signal at the output of potentiometer **124.** A further increase in KV causes Zener diode **112** to conduct and so places resistor **118** in parallel with resistors **116** and **120.** The total effect is to produce a signal output directly proportional to input KV with three constants of proportionality diminishing with increasing KV. The KV compensation circuit **100** is non-linear because at higher KV values, the X-ray tube filament **12** needs less temperature change to hold a constant anode current for a given change in KV.

The desired anode current (MA) reference signal is developed from a regulated negative supply potential (−6.8 volts) applied to terminal **132.** A plurality of preset voltages are selectable by means of a preset select switch **134** respectively coupled to the wipers of potentiometers **136, 138, 140 . . . 142.** The selected preset voltage at switch **134** is for use in the "RAD" mode and is applied to a Rad-Fluoro switch **144.** The movable contact of switch **144** is coupled to switch contacts **146** through resistor **148.** The switch contacts **146** are coupled to circuit lead **150** which in turn is coupled to the summing resistor **53** shown in FIG. **5.** The switch **146** is normally open and is made to close **1.0** second before a radiographic exposure whereupon a predetermined filament current before exposure is set by potentiometers **136 . . . 142** selected by switch **134.**

In the "Fluoro" mode, the desired MA signal is developed across two potentiometers **152** and **154** which are connected between terminal **132** and ground and whose respective wiper arms are coupled to a third potentiometer **156.** The wiper arm of potentiometer **156** is connected back to a switch **144.** The fluoro configuration is utilized such that the wiper arm of potentiometer **152** is set at one limit while the wiper arm of potentiometer **154** is set at another limit and the output as determined by potentiometer **156** being selectable between these limits. Thus depending upon whether the RAD or Fluoro mode is used a selected negative potential is applied to the summing resistor **53** in FIG. **5** during an X-ray exposure time.

The means for providing the reference signal corresponding to the actual MA is developed by means of

the "drop wire" resistance method as previously illustrated in FIG. 6. In the present embodiment, however, the actual MA signal is developed from secondary winding 15 of transformer 17 rather than transformer secondary 16 as heretofore required. The reason for this will be shown subsequently. However, such a signal can be developed across winding 15 while winding 16 is grounded. Accordingly, in the present embodiment the end of secondary winding 15 opposite from that coupled to the filament 12 is coupled by means of circuit lead 158 to a selector switch 160 which has its wiper arm selectively connected to a plurality of drop wire resistances generally designated by reference numeral 162. These drop wire resistances each comprise a fixed resistor and a rheostat coupled in series to ground. The switch 160 is ganged with the preset selector switch 134 such that the value of the drop wire resistance is varied in accordance with the selected voltage for the desired MA. A voltage corresponding to the actual MA appears at junction 164 which is common to a resistor 166. A second resistor 168 is coupled to the opposite side of resistor 166 and a negative (−) bias potential is applied to terminal 170. The purpose of the negative bias potential applied to terminal 170 is to offset the actual MA signal appearing at junction 164 such that when the MA is as expected, depending on the setting of switch 160, the voltage appearing at circuit junction 172 will be zero. A switch 174 couples circuit junction 172 to a circuit lead 176 connected to the summing resistor 54 in FIG. 5. Switch 174 is made to close 0.1 second after switch 23 is closed to permit the actual MA signal to appear at junction 164 so as to avoid transient response for zero MA.

In operation, the positive KV compensation input signal is continuously applied to summing resistor 52 of FIG. 5. The negative voltage selected for the desired MA signal is applied to summing resistor 53 1.0 second prior to exposure and is algebraically summed with the KV compensation signal and the positive voltage corresponding to the average signal D applied to summing resistor 51 for effecting a preset value of filament current. The algebraic difference signal at the output of the summing amplifier 50 in combination with the sawtooth signal applied to the level detector 60 causes the switch 4 to fire at the proper time to cause a null condition to exist at the summing point comprising the common junction between resistors 51, 52, 53 and 54. After 0.1 seconds after the start of exposure the difference signal between the actual MA signal appearing at junction 164 and the negative reference bias potential applied to terminal 170 appears at junction 172 and is also applied to the summing point by means of resistor 54; however, as noted above, if the actual MA signal is as expected due to the setting of switch 60, the voltage applied to resistor 54 will be zero. If on the other hand the actual MA is too high, a positive voltage will be applied to resistor 54 and if too low, a negative voltage. Accordingly if any of the input signals to the summing amplifier 50 decreases, the output thereof will increase, causing the voltage detector to trip earlier and thus cause an earlier firing angle of the switch 4. For example, for a decrease in the actual MA, the voltage at junction 164 drops and a negative signal would appear on circuit lead 176 connected to summing resistor 54. The input to the summing amplifier 50 would thus decrease, but its output signal will increase causing the switch 4 to fire earlier, and thus increase the actual MA signal. Thus any change in the control loop will be sensed and an error signal of proper polarity and magnitude will be produced which will cause the switch 4 to fire accordingly to cause the inputs to the summing amplifier to establish a null condition.

Thus the filament current before exposure is set by the desired MA signal and during exposure by the actual MA difference or error signal at resistor 54. Switch 146 is arranged to close 1.0 second or more before exposure to allow the tube filament to heat to the required temperature. For best tube life, the filament is maintained at the lowest possible temperature until 1.0 second or more before the actual exposure.

It is readily apparent that the present invention provides a lightweight inexpensive means for controlling X-ray emission by regulating the RMS current to the X-ray generator filament. The need for filament load resistors and the constant voltage line regulators required in previous systems has been eliminated. Not only has the expense been greatly reduced, but the time delay response has been considerably shortened over previous systems.

While the present invention has been described with a degree of particularity for the purpose of illustration, it is to be understood that all modifications, substitutions, and alterations within the spirit and scope of the present invention are herein meant to be included. For example, while the RMS regulator of the present invention has been described for the purpose of controlling X-ray generator filament temperature, it is to be understood that the RMS regulator of the present invention is equally applicable to temperature control of any load, such as heating elements or incandescent lights. Temperature control is obtained by modulating the RMS current through such a load.

We claim as our invention:

1. An RMS current regulator for controlling the filament power to an X-ray generator having a filament and an anode, comprising in combination:
- switching means responsive to a firing signal for controlling the current through said filament;
- current responsive means for providing a signal proportional to the current through said filament;
- means for squaring said signal;
- means for averaging the squared signal; and
- comparing means responsive to a comparison of the average signal and at least one of three X-ray generator operation signals representative of anode voltage, desired anode current and actual anode current, respectively, as a reference input signal for firing said switching means to control the RMS current to said filament in response to an error signal provided by said comparing means.

2. The combination of claim 1 wherein said comparing means includes summing amplifier means responsive to the average signal and reference input signals representative of the desired anode current and the actual anode current for providing an algebraically summed error signal;
- means for providing a sawtooth waveform synchronized to the power line feeding said X-ray generator; and
- means responsive to the algebraic sum of said sawtooth waveform and the error signal from said summing amplifier means for providing said firing signal to said switching means.

3. The combination of claim 2 wherein said summing amplifier means is additionally responsive to a reference signal comprising the anode voltage for providing compensation for variations in anode voltage due to anode tranformer or line regulation.

4. The circuitry of claim 2 wherein said means for providing said firing signal includes a blocking oscillator for firing said switching means and a level detector means responsive to said sum for actuating said blocking oscillator means.

5. The combination of claim 2 wherein said means for providing a sawtooth waveform includes a sawtooth generator operating at a frequency twice the power line frequency.

6. The combination of claim 1 wherein said switching means is a bidirectional silicon switch.

7. The combination of claim 1 wherein said current responsive means includes a bridge rectifier and a current transformer interconnecting said bridge rectifier to the filament circuit.

8. The combination of claim 7 wherein said means for squaring includes a network for approximating the square of the output from said bridge rectifier.

9. The combination of claim 1 wherein said means for averaging includes an integrator for obtaining a DC signal which is proportional functionally to the RMS value of actual filament current.

10. The combination of claim 9 wherein said DC signal is direclty proportional to the square of the RMS value of the filament current.

11. The combination of claim 1 wherein the power to more than one filament within the same X-ray generating tube is to be controlled including:

at least one additional filament and semiconductor switching means to control current therethrough; and

multivibrator means for firing the switching means connected to the unused filament to provide an idling current to the unused filament.

12. The apparatus of claim 12 wherein said multivibrator means provides a delayed firing pulse to the switching means which fails to receive a firing signal from said firing means.

13. An RMS current regulator for controlling power applied to a load such as an X-ray tube filament comprising, in combination:

semiconductor switching means responsive to a firing signal for controlling current through said load;

means providing a signal corresponding to a measurement of the instantaneous value of current through said load;

means for squaring said signal;

means for filtering the squared signal to obtain a DC signal directly proportional to the square of the RMS current through said load; and

operational amplifier means for algebraically summing said DC signal with reference input signals comprising signals representative of the desired load current and the actual load current for firing said semiconductor switching means to control the RMS current through said load.

14. A method of controlling the current and therefore the temperature of a filament type load by modulating RMS current through the load with a semiconductor switch comprising the steps of:

sampling the instantaneous current through said semiconductor switch and providing a signal thereof;

squaring said signal;

filtering the squared signal to obtain an average signal thereof; and

comparing the average signal to signals indicative of the desired load current and the actual load current to control the firing of the semiconductor switch.

15. The method of claim 14 wherein the step of comparing includes the step of first comparing the average signal sample to a reference signal which is a function of the algebraic summation of the anode voltage of an X-ray tube, the desired anode current of said X-ray tube, and the actual anode current of said X-ray tube, and comparing the result of said first comparison to a sawtooth waveform which is synchronized to the power line.

* * * * *