Nov. 29, 1960 P. A. DUFFY, JR 2,962,594

X-RAY APPARATUS

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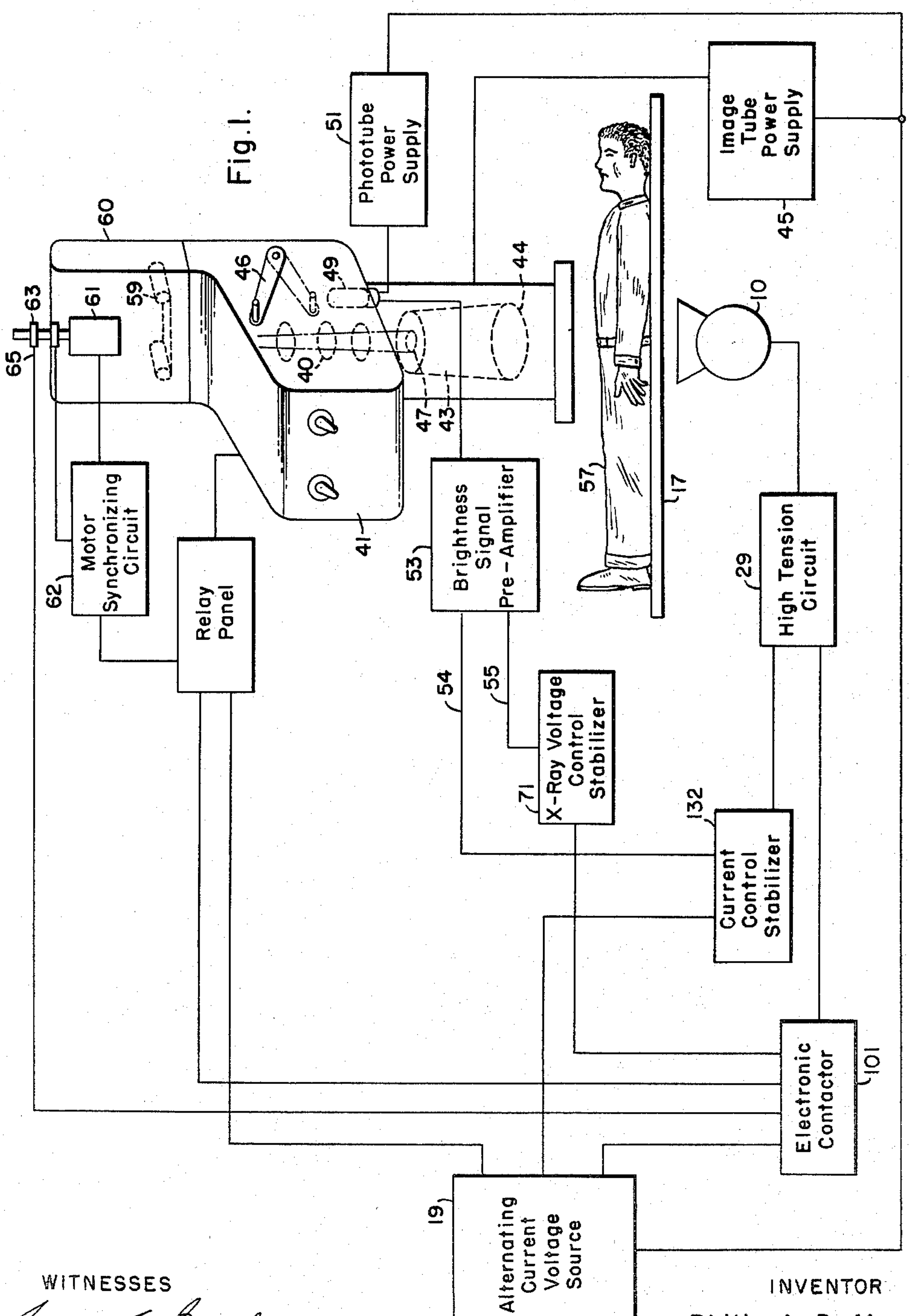

Fig. 1.

WITNESSES

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X-RAY APPARATUS

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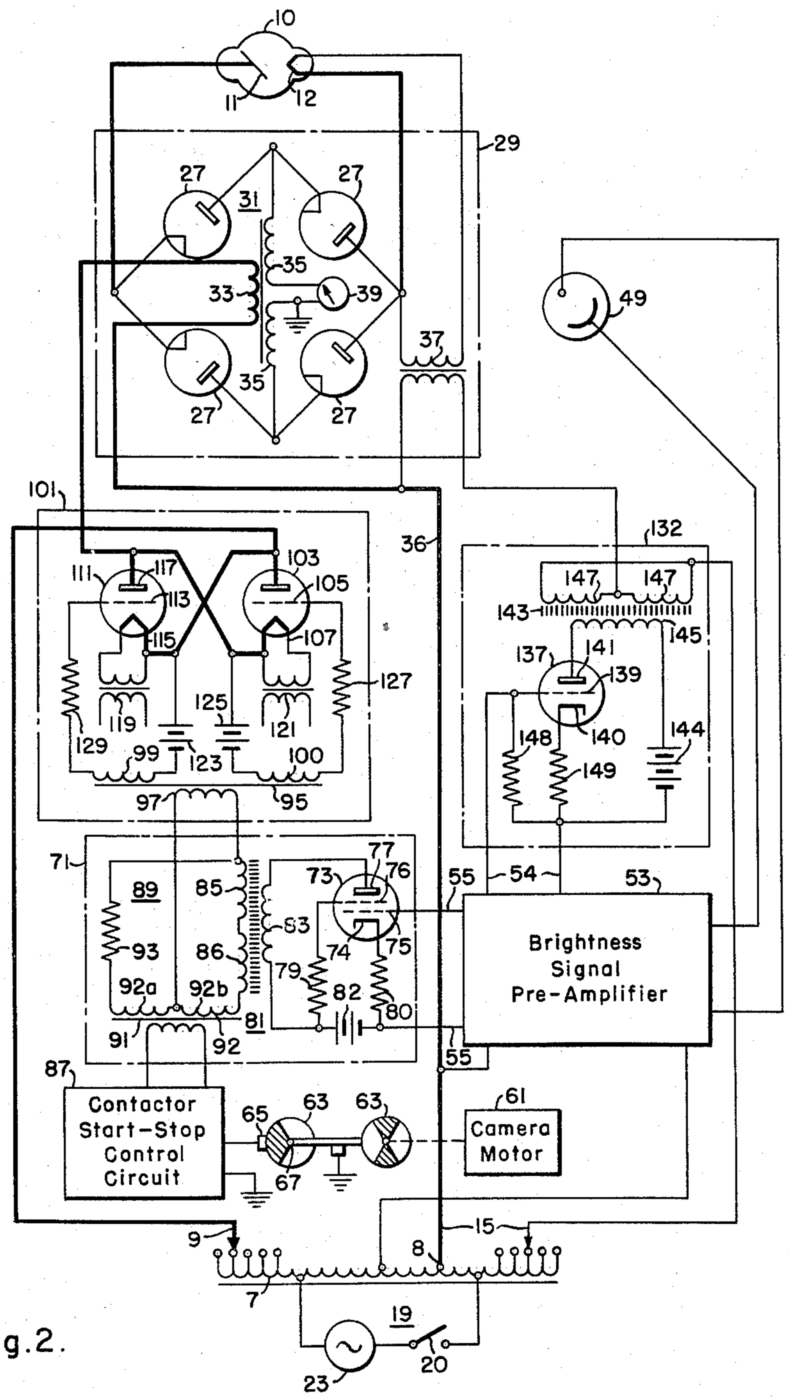

Fig. 2.

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Fig.3.

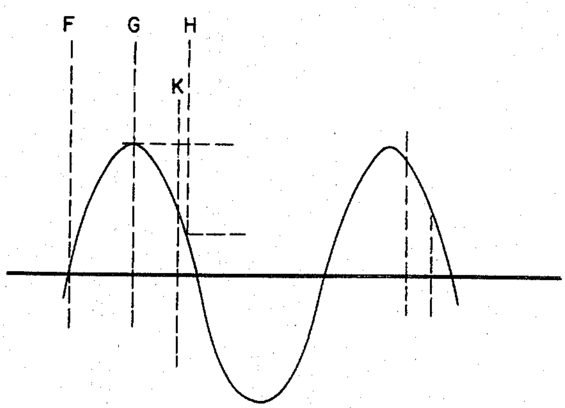


Fig.4.

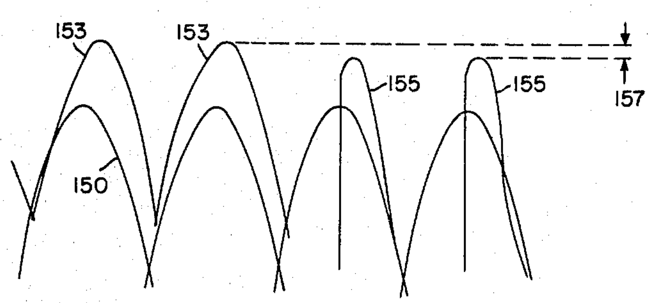


Fig.5.

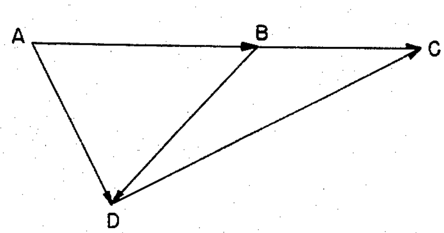
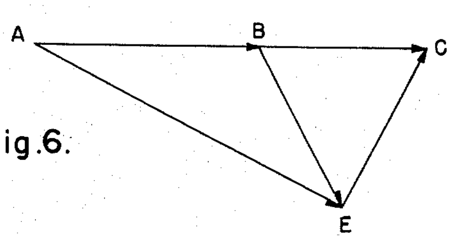


Fig.6.



United States Patent Office

2,962,594

Patented Nov. 29, 1960

2,962,594

X-RAY APPARATUS

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Filed Sept. 14, 1956, Ser. No. 609,900

16 Claims. (Cl. 250—95)

The present invention relates to improved X-ray apparatus and more particularly to an improved control to maintain substantially constant brightness of the resultant X-ray picture.

In X-ray apparatus including a fluorescent screen for providing a visible image, there is a problem of maintaining the brightness of the visible image substantially constant as different thicknesses of objects are subjected to the X-rays or when objects having varying X-ray opacity are scanned by the X-ray beam. The same problem also arises when the X-ray apparatus is used in the process of making motion pictures of the fluorescent image and where the area of the object subjected to the X-ray beam is changed to a different area having a new thickness or where material having a different opacity is moved into the field of the X-rays during the exposure of successive frames of motion picture film. Even when every effort is made to accurately predict the X-ray tube voltage and current requirements prior to initiation of photographic sequence, it has been found that a given strip of motion picture film will vary from under-exposed frames to over-exposed frames in the course of a single sequence.

In the first experimental efforts to solve the foregoing problem apparatus was employed in which a phototube responsive to the image brightness was connected to circuitry for varying the X-ray tube filament voltage supply so as to control the X-ray tube milliamperage in inverse proportion to the image brightness. While that experimental system rendered a considerable improvement in brightness stability, it was found that substantial constancy of image brightness during a normal fluoroscopic medical examination would require variation of the X-ray tube current over a range of 100 to 1. Such a wide variation of X-ray tube current is prohibited by the capacity limitations of practical X-ray generators and is further precluded by biological radiation safety requirements.

An X-ray tube requires a high voltage for its operation. One conventional source of high voltage is a circuit comprising a high tension transformer and a plurality of rectifier devices. The low voltage primary of the transformer is ordinarily connected to a commercial voltage source, and the high tension secondary winding of the transformer is connected through a bridge rectifier circuit to the cathode and anode of the X-ray tube.

Accordingly, it is an object of the present invention to provide an improved control for the X-ray tube voltage or power source.

It is another object of the present invention to provide improved X-ray apparatus including a brightness stabilizing circuit responsive to the intensity of the visible fluorescent image.

It is a further object of the present invention to provide an apparatus for continuously controlling the intensity of an X-ray beam.

It is an additional object to provide a brightness stabilizing circuit for an X-ray apparatus having a power source including a high tension transformer with an associated rectifier circuit for supplying unidirectional current to an X-ray tube.

It is a different object to provide a brightness stabilizing system for X-ray apparatus which includes two separate and cooperative means for varying the intensity of the X-ray beam with one of said means being operative to control the voltage applied to the X-ray tube and with the other of said means being operative to control the anode current conducted by the X-ray tube.

It is a still further object to provide an X-ray apparatus utilizing an electronic contactor controlled by an image brightness responsive means which is capable of producing X-ray exposures having a time duration of less than 1/120 of a second.

It is still another object to provide an X-ray apparatus utilizing an electric contactor controlled by a photosensitive device to variably control the voltage applied to the X-ray tube in inverse response to the intensity of an X-ray beam penetrating an object.

These and other objects and advantages of the invention will be apparent during the course of the following description. The invention, however, both as to its organization and method of operation will be best understood from the following description when read in connection with the accompanying drawings in which:

Figure 1 is an illustrative block diagram of apparatus in accordance with the present invention;

Fig. 2 is a detailed schematic diagram of significant portions of the apparatus in accordance with the present invention;

Figs. 3 and 4 are wave-shape diagrams illustrating the manner in which voltage is applied to the X-ray tube power supply circuit, and

Figs. 5 and 6 are vector diagrams illustrating the operation of a portion of the control circuit in accordance with the present invention.

Referring now to Fig. 1, there is shown an X-ray generator comprising an X-ray tube **10**, a high voltage rectifier circuit **29** and an alternating current voltage source **19**. The voltage source may be an autotransformer **7** having a plurality of output terminals and having its input terminals connected through a circuit breaker **20** to a suitable commercial source of alternating current power **23**, as shown in Fig. 2. Serially connected between the alternating current voltage source **19** and the high voltage rectifier circuit **29** is an electronic contactor **101** which may comprise a pair of inverse parallel connected thyratron tubes.

Adjacent the X-ray tube **10** is positioned an object support member **17** for supporting a patient or object **57** in a position for projecting a beam of radiation through the object from the X-ray tube **10**. As in the usual arrangement the X-ray tube **10** may be movably mounted to traverse a plane of considerable area adjacent to the support surface **17**. Adjacent the support surface **17** on the opposite side thereof from the X-ray tube is located an image intensifier device **43** having a fluorescent image-forming screen **47**. The image intensifier tube **43** is shown diagrammatically and comprises essentially a preferably cylindrical container having at one end an X-ray sensitive and photoelectric emissive screen **44**. An electron image created by the photoelectric screen **44** is projected to an electron sensitive fluorescent screen member **47** where it produces a visible image of reduced dimensions and increased brightness corresponding to the X-ray image projected on the X-ray sensitive screen **44**. An image intensifier of a type which may be used in the present apparatus is described in detail in Mason et al. Patent 2,523,132.

An optical focusing means **40** contained within a housing **41** is positioned adjacent the image intensifier tube **43** and operates to focus an image from the fluorescent screen member **47** to the film plane of a moving picture camera positioned in optical relation to the image intensifier tube **43** and the optical focusing means **40**. The motion picture camera **60** includes a film transport mechanism **59** and is operative to intercept a light image projected from the fluorescent screen member **47** so as to expose successive frames of the film within the camera **60**. A synchronous motor **61** is provided for driving the film transport mechanism **59** of the camera **60**. Operatively connected to the synchronous motor **61** and the film transport mechanism are a plurality of commutator type switch devices **63** each having an angular conductive portion **67**, Fig. 2, and a cooperative brush **65** to provide cyclical voltage pulses in synchronism with the positioning of successive film frames at the focal plane of the camera **60**. The voltage pulses provided by the commutator switch **63** are transmitted to an electronic contactor **101** and are there operative to control conductivity of the contactor, such that the contactor **101** will energize the X-ray generator only during successive intervals when the film in the motion picture camera **60** is properly positioned for exposure.

A light responsive member or photosensitive means **49** is positioned relative to the fluorescent screen member **47** so as to intercept a portion of the visible light emanating from the screen **47** and is operative to produce an electrical signal responsive to the brightness of the visible image on the fluorescent screen member. The light responsive member **49** may be a photosensitive electron tube of the photomultiplier type, such as the RCA type 931A. The photomultiplier tube **49** is provided with energizing voltage by conventional power supply **51** of the type normally used with such tubes. The light responsive member **49** is connected to a brightness signal preamplifier circuit **53** which will be discussed in further detail hereafter. A first output signal **55** of the brightness preamplifier circuit **53** is connected to an X-ray tube voltage control brightness stabilizer circuit **71**, which is in turn connected to the electronic contactor **101** so as to control the average conductivity of the electronic contactor. More specifically, the voltage control brightness stabilizer circuit **71** is responsive to a signal proportional to the brightness of the light image at the fluorescent screen member and operates to impose a control voltage component on the electronic contactor **101**, so as to control the period of cyclical conductivity of the contactor **101**, thereby controlling the voltage applied to the X-ray tube **10** in inverse response to the brightness of the fluorescent light image at the fluorescent screen member **47**.

A second output signal **54** of the brightness preamplifier circuit **53** is connected to an X-ray tube current control brightness stabilizer circuit **132**. The current control brightness stabilizer circuit **132** may be a circuit similar to that shown by Weisglass Patent 2,319,378, or may be other known power amplifier circuits which are adapted to control the current in an A.C. circuit in inverse response to variations in a D.C. signal voltage **54** applied as from the brightness signal preamplifier circuit **53**. The current control brightness stabilizer circuit **132** is serially connected between a filament current supply source **15**, Fig. 2, and the filament energizing circuit for the X-ray tube **10**. By variation of an impedance **143** connected in series with the filament supply circuit the electron emission of the X-ray tube filament **12** is controlled in inverse relation to the brightness of the image appearing at the fluorescent screen member **47**, thereby controlling the current conducted by the X-ray tube **10** in inverse relation to the brightness of the visible image.

Referring now in detail to Fig. 2, the X-ray tube **10** including an anode **11** and a filament **12** is connected through a full-wave voltage rectifying circuit **29**, comprising a plurality of high voltage rectifiers **27**, to the secondary winding **35** of a high tension transformer **31**. The high tension secondary winding comprises two winding sections **35** which are connected in series through a milliampere meter **39** or a metering circuit of a well-known type. The end of one of the secondary winding sections which is connected to the milliampere meter may be and is preferably grounded. The secondary windings **35** of the high tension transformer **31** are connected to the full-wave rectifier circuit in series additive relation, such that the voltage applied to the rectifiers is substantially the sum of the voltages of the two secondary winding sections.

The primary winding **33** of the high tension transformer **31** has one terminal connected, through conductor **36**, directly to a suitable terminal on the power supply autotransformer **7**. The other end of the high tension transformer primary is connected through the electronic contactor **101** to an adjustable tap **9** on the power supply autotransformer **7**. Further included in the X-ray generator high tension circuit **29** is an V-ray tube filament energizing isolation transformer **37**, which has its secondary winding at a high D.C. voltage level corresponding to the direct current voltage impressed upon the filament **12** of the X-ray tube **10**, and which has its primary winding near ground potential with one end of the primary winding being connected directly to the common terminal **8** of the voltage supply autotransformer **7** by means of the common conductor **36**. The other end of the X-ray tube filament transformer primary is connected through the A.C. windings **147** of a saturable reactor **143** in the current control brightness stabilizer circuit **132**, and thence to a suitable terminal of the voltage supply autotransformer **15**.

The light responsive member **49** shown diagrammatically in Fig. 2 is physically positioned, as shown in Fig. 1, in optical relation to the fluorescent screen member **47** so as to be responsive to the brightness of the visible light image appearing on the fluorescent screen member **47** and is operative to produce a direct current signal proportional to the brightness of the visible image. The direct current signal from the photoelectric light responsive means **49** is fed to the input of the brightness signal preamplifier **53**.

The brightness signal preamplifier circuit **53** is not shown in detail and may comprise any of a large number of well-known D.C. voltage amplifiers having a high input impedance and having a low output impedance and being operative to produce a D.C. voltage proportional to the amplitude of a D.C. current fed into the input. The only essential criteria for a D.C. amplifier for use in the present apparatus is that it be reasonably stable and free from drift in its output voltage when the input current is zero, and free from drift in amplification factor.

The brightness signal preamplifier **53** is provided with two similar output circuits **54** and **55**, with one output circuit **55** being connected across the grid-cathode circuit of a discharge device **73** in the X-ray tube voltage control stabilizer **71**, and with the other output circuit **54** being connected across the grid-cathode circuit of a discharge device **137** in the current control brightness stabilizer circuit **132**.

The current control brightness stabilizer circuit **132**, which is provided with an input signal from the brightness preamplifier **53** and which is operative to control the voltage applied to the primary winding of the X-ray tube filament heating transformer **37**, comprises a electron discharge device **137**, preferably of the vacuum type type, having an anode **141**, a control electrode or grid **139**, and a cathode **140**. The current control brightness stabilizer circuit **132** further includes a saturable reactor **143** having a direct current control winding **145** which is connected in series with the anode circuit of the power amplifier discharge device **137** and in series with a suitable direct current voltage source **144**, shown schematically as a battery, but which may be any conventional type of direct current power source. The saturable reactor **143** includes a pair of alternating current windings **147** which are connected in parallel and in voltage opposing relationship with respect to winding **145** and the parallel combination is connected in series with the X-ray tube filament heating circuit comprising voltage source **15** and the primary winding of transformer **37**. The input signal to the current control brightness stabilizer circuit **132** from the brightness signal preamplifier **53** is connected across a grid resistor **148** and is connected to the grid **139** of the power amplifier discharge device **137**. The cathode **140** of the discharge device **137** is connected through a cathode biasing resistor **149** to the common side of the brightness signal preamplifier output circuit **54** and to the negative side of the direct current voltage source **144**.

As the D.C. output voltage **54** from the brightness signal preamplifier **53** increases in response to an incremental increase in intensity of the visible image at the fluorescent screen member **47**, the control electrode **139** of the power amplifier discharge device **137** is driven more negative with respect to the cathode **140**, thereby inducing a decreased current flow to the anode **141**, and through the D.C. winding **145** of the saturable reactor member **143**. The imposition of that negative component of direct current upon the D.C. control winding **145** of the saturable reactor operates to decrease the saturation of the magnetic core of the saturable reactor **143**, thereby increasing the impedance of the alternating current windings **147**. The increased impedance in the A.C. windings causes an accompanying increase in the voltage drop across the alternating current windings **147**, thereby applying a reduced alternating current voltage to the primary winding of the filament heating transformer **37**. The reduced voltage thus applied to the X-ray tube filament **12** induces a decrease in electron emission from the X-ray tube filament **12** so as to result in a reduced anode current through the X-ray tube **10** and the high voltage rectifier circuit. Thus, an incremental increase in brightness results in an accompanying decrease in X-ray intensity. It is to be noted that X-ray tubes conventionally operate at filament saturation so that the anode current is a function principally of the filament excitation as well as being secondarily a function of the voltage applied between the cathode and the anode.

During the course of a fluoroscopic examination the diagnostician frequently observes some organic function or malfunction in the anatomy of the patient of which it is desirable to provide a permanent photographic record to substantiate the fleeting fluoroscopic observation. For example, a suspected ulcer in the duodenal portion of the small intestine is often times observed for only a fleeting interval during the examination. Likewise, it is frequently desirable to provide a strip of motion picture film recording the different phases of the patient's heart action. To be successful, apparatus for providing such a photographic record must be instantly operable and available without distracting the fluoroscopist from the image being examined.

In the apparatus of the present invention, the photographic recording means comprises a motion picture camera **59** contained within a housing **60**, the driving motor **61** for the camera film transport mechanism, a motor synchronizing circuit **62** for insuring that the motor **61** is synchronized in phase with the voltage pulses applied to the X-ray tube **10**, a manual switch member **46** on the optical device housing **41**, and relay means connected between the said switch member **46**, the motor synchronizing circuit **62** and the electronic contactor **101**.

In order to initiate motion picture photography, the operator moves the manual control member **46** on the optical device housing **41** from the uppermost position, as shown in Fig. 1, to the lowermost position, as shown in dotted lines in Fig. 1. Actuation of the control member **46** operates suitable switches (not shown) within the optical device housing **41** to energize suitable relays so as to initially energize the camera driving motor **61**. As shown in Fig. 2, the camera motor **61** has connected thereto a plurality of commutators **63**, each of which is of insulating material and has an angular conductive segment **67** on its periphery. One of the said commutator switches **63** together with a brush **65** in contact with the commutator and together with the contactor start-stop control circuit **87** comprises a first contactor control circuit for controlling the conductivity of the electronic contactor **101**. As the camera motor **61** operates, the commutator **63** rotates to periodically complete a circuit from the contactor start-stop control circuit **87** through the brush **65** and the conductive segment **67** to ground. As seen in Fig. 2, it may be considered that the rotating commutator **63** provides periodic pulses to the contactor start-stop control circuit **87** in synchronism with the positioning of successive film frames at the focal plane of the camera **59**. The said periodic pulses are operative to cause the contactor control circuit **87** to apply an alternating current voltage to the primary of a control transformer **91**. The details of the contactor control circuit **87** are not shown in the present application in that arrangements for the control of inverse parallel thyratron contactors are known in the art. A start-stop control circuit of a type suitable for use in the present apparatus is shown by U.S. Patent 2,785,343, of R. L. Wright et al., issued March 12, 1957, for X-Ray Apparatus, and assigned to the assignee of the present invention. Such a contactor start-stop control circuit **87** is operable to apply an alternating current voltage to the primary winding of the contactor start transformer **91** during the time periods in which a control circuit is closed through the rotating commutator **63**. The start-stop control circuit is further operative to insure the application of voltage to the contactor start transformer **91** at the beginning of the next succeeding half cycle of the alternating current supply voltage. The contactor start control circuit **87** is necessary in order to assure that voltage will not be applied to the contactor start transformer **91** at the peak of a half cycle of the A.C. supply voltage, but will be initially energized only at the beginning of the first half cycle of applied voltage after the closing of the commutator switch **63**, regardless of when the commutator switch **63** is first closed with reference to the supply voltage wave. The electronic contactor **101**, shown in block diagram form in Fig. 1, is shown in detail in Fig. 2 as comprising a pair of inverse parallel connected discharge devices **103** and **111**, each having an anode, a cathode, and a control electrode, and further comprising a filament heating transformer **119**, **121** for each of the thyratron discharge devices **103** and **111** and a bias voltage supply **123**, **125**. A grid control transformer winding **99**, **100** and a grid resistor **127**, **129** are connected in series between control electrode **113** and the cathode **115** of each of the thyratron discharge devices **103** and **111**. The first **103** and second **111** inversely connected thyratron tubes are connected together in inverse parallel relation and the parallel combination is connected in series with the primary winding **33** of the high tension transformer **31** across suitable taps **8** and **9** on the autotransformer voltage supply source **7**. The first thyratron tube **103** is cyclically controlled by an alternating current voltage applied to its control electrode **105** by a first grid control secondary winding **100** of a signal input coupling transformer **95**. The second thyratron is similarly controlled by a voltage applied to its grid **113** from a second secondary winding **99** of the signal input coupling transformer **95**. The bias voltage supplies **123** and **125**, connected in series with the signal input secondary windings **99** and **100** are effective to maintain the respective thyratron tubes non-conductive so long as no alternating current voltage is applied to the grids **105** and **113** from the input signal coupling transformer **95**. The bias voltage supplies **123** and **125** shown in Fig. 2 as batteries, may of course comprise a more complex D.C. bias voltage supply means such as the type shown in the aforementioned U.S. Patent 2,785,343. By applying a control voltage from the coupling transformer secondary winding 100 to the control electrodes 105 and 113 of the thyratron discharge devices 103 and 111, they are caused to conduct either during the entire period in which their anodes 109 and 117 are positive with respect to their cathodes 107 and 115, or by shifting the phase of the voltage applied to the transformer 95, the thyratron discharge devices 103 and 111 may be caused to conduct for any selected lesser portion of the period during which their anodes 109 and 117 are positive with respect to their respective cathodes.

In Fig. 2 the X-ray tube voltage control brightness stabilizer circuit 71 is shown as including a phase shift circuit 89 which comprises alternating current windings 85 and 86 of a saturable reactor 81, the center-tapped secondary 92 of the contactor start transformer 91, and a phase shift resistor 93 connected in series relationship in a closed loop circuit. The two alternating current windings 85 and 86 of the saturable reactor 81 are connected in opposing relationship in a manner well known in the art so that no alternating current voltage is coupled from the two secondary windings 85 and 86 into the D.C. control winding 83 of the saturable reactor 81. The primary winding 97 of the control signal coupling transformer 95 is connected across the phase shifting network 89 with one end of the primary winding 97 being connected to the center tap of the secondary winding 92 and with the other end of the primary winding 97 being connected to the closed loop circuit at the connection between the phase shifting resistor 93 and the alternating current winding 85 of the saturable reactor 81.

An alternating current control signal which is applied to the contactor start transformer 91 from the contactor start-stop circuit 87 is coupled through the phase shifting network 89 to the primary 97 of the control signal coupling transformer. Current flow in primary 97 induces corresponding voltages in secondary windings 99 and 100 and said voltages are applied in opposing phase relationship to the respective grids 105 and 113 of the first and second thyratron tubes 103 and 111 in the electronic contactor. By varying the impedance of the alternating current windings 85, 86 of the saturable reactor 81, it is possible to vary the phase relationship of the voltage applied to the control electrodes 105 and 113 of the thyratrons. The precise manner in which the phase shift network 89 operates to control the conductivity of the contactor will be set forth in further detail hereafter.

The X-ray tube voltage control brightness stabilizer circuit 71 further comprises an electron discharge device 73 having a control electrode or grid 75, a screen grid 76, a cathode 74 and an anode 77. A second output signal 55 from the brightness preamplifier circuit 53 is connected to the grid 75 of the discharge device so as to apply a direct current voltage component corresponding to the brightness of the visible image between the control electrode 75 and the cathode 74. The anode 77 of the discharge device 73 is connected to a direct current voltage supply source 82 through the D.C. control winding 83 of the saturable reactor 81. The screen grid 76 of the discharge device is connected to the same direct current voltage supply source 82 through a voltage dropping resistor 79. The cathode 74 of the discharge device 73 is connected to the negative side of the direct current voltage supply source 82 through a cathode biasing resistor 80 and the negative side of the direct current voltage supply source 82 is further connected to the common side of the brightness signal preamplifier second output circuit 55.

When an incremental change occurs in the brightness of the visible image appearing at the fluorescent screen member 47, the photoelectric means 49 transmits a component of D.C. signal current to the brightness signal preamplifier circuit 53. The brightness signal preamplifier circuit 53 is responsive to that change in brightness signal current to cause the imposition of a voltage component upon the grid 75 of the discharge device 73 and to thereby cause a proportional change in the anode current flowing through the discharge device 73 and through the D.C. control winding 83 of the saturable reactor 81. The saturable reactor thus constitutes a variable impedance device which responds to the component of D.C. current imposed upon its D.C. control winding 83. Upon an increase in the current through the D.C. control winding 83 the saturation of the reactor 81 increases, thereby causing a decrease in the impedance of the alternating current windings 85 and 86.

When a reactor, such as the alternating current windings 85 and 86 of the saturable reactor, is connected across an A.C. voltage source, such as the center-tapped secondary winding 92, the current in that reactor will lag the applied voltage by an angle approaching 90 electrical degrees. In contrast, if a resistor, such as the phase shifting resistor 93, were connected directly across the A.C. voltage source, the resistor would pass current in phase with the applied votlage. When the phase shifting resistor 93 and the saturable reactor alternating current windings 85 and 86 are connected in series across an alternating current voltage source such as secondary winding 92 in Fig. 2, the same alternating current flows through both the resistor 93 and the alternating current windings 85 and 86. The alternating current voltage drop across the resistor 93 lags approximately 90 electrical degrees behind the voltage drop across the reactor 81, with the voltage drop of the resistor and the voltage drop of the reactor being vectorially additive to equal the A.C. voltage applied by the secondary winding 92 of the contactor start transformer 91.

Figs. 5 and 6 are vector diagrams illustrating, respectively, the phase relationship of the various voltages in the phase shifting network for the unsaturated and for the saturated condition of the saturable reactor member 81. In Fig. 5 is shown the phase relationship of the various voltages for the condition in which the reactor member 81 is relatively unsaturated and has a relatively high impedance. The vector AB represents the alternating current voltage appearing across one section 92*a* of the secondary winding 92. The vector BC represents the alternating current voltage provided by the second winding section 92*b* of secondary winding 92. The vector AD represents the A.C. voltage appearing across the phase shifting resistor 93 and the vector DC represents the voltage appearing across the alternating current windings 85 and 86 of the variable impedance member 81. From the foregoing and from Fig. 5, it may be seen that the alternating current voltage applied to the primary 97 of the signal coupling transformer 95 is represented by the vector BD, and is equal to the vector sum of the voltages appearing across winding section 92*b* and across the A.C. windings 85 and 86 of the saturable reactance impedance member 81. It is to be noted that when the impedance of the alternating current windings 85 and 86 of the saturable reactor is near a maximum, the vector DC representing the voltage across that reactance 81 is much larger than the vector AD representing the voltage across the phase shifting resistor 93. As a result, the vector BD representing the voltage applied to the coupling transformer 95 lags the input voltage AB by approximately 130 electrical degrees.

In Fig. 6 is shown the vector diagram of the various voltages appearing in the phase shifting network 89 in the condition wherein the reactor member 81 is highly saturated by an increased direct current flowing through the D.C. control winding 83 of the reactor member. The vector AB again represents the voltage appearing across winding section 92*a* and the vector BC again represents the voltage appearing across winding section 92*b*. The vector AE represents the voltage appearing across the phase shifting resistor 93 and the vector EC represents the voltage appearing across the alternating current windings 85 and 86 of the saturable reactor member 81. The vector sum of the voltage AE across the phase shifting resistor **93** and the voltage EC across the saturable reactor is equal to the voltage applied by secondary winding **92**. The voltage applied to the primary winding **97** of the coupling transformer **95** is now represented by the vector BE. The vector EC is now much shorter than the vector AE because the impedance of the alternating current windings **85** and **86** has decreased and is now smaller than the impedance of the phase shifting resistor **93**. The vector BE representing the votlage applied to the primary winding **97** of the coupling transformer **95** now lags the vector BC by approximately 60 degrees. Thus, it is seen that by imposing a component of D.C. current upon the D.C. control winding **83** of the saturable rector member **81**, the phase of the voltage applied to the primary winding **97** of the coupling transformer has been shifted through approximately 70 electrical degrees, and hence the alternating current voltages applied to the respective grids **105** and **113** of the inversely connected thyratrons **103** and **111** has been shifted approximately 70 degrees with respect to the alternating current voltages applied to the anodes **109** and **117** of the respective thyratrons. By proper choice of component values in the phase shifting network **89**, it is possible to cause the voltages induced in secondary winding **99** and secondary winding **100** to be so phased that the grid **105** of the thyratron discharge device **103** will become positive with respect to the cathode **107** at approximately the 90° point of the voltage wave applied to the anode **109**. With that condition existing, the thyratron discharge devices **103** and **111** will each begin to conduct at approximately the 90° point of their respective anode voltage waves and will continue to conduct so long as the anode is positive with respect to the cathode, or for about 90 electrical degrees from the 90° point to the 180° point of the anode voltage wave.

It was previously considered important to make the firing point of thyratron contactors occur as closely as possible to the zero point of the anode voltage wave in order to avoid the generation of transient voltages in the high tension transformer of an X-ray machine. I have found that in the use of an electronic contactor to control the cinefluorographic apparatus of the present invention the portion of the wave from zero to 90 electrical degrees applied to the primary of the high tension transformer contributes a negligible amount of energy to the visible image appearing on the fluorescent screen member. I have further found that the formerly apprehended transient voltages do not occur unless the X-ray tube current is reduced to an unusual minimum. Thus, it is advantageous to apply voltage to the primary of the high tension transformer **31** only during the period from 90 electrical degrees to 180 electrical degrees of the supply source wave, thereby reducing the radiation impinging upon the patient and similarly reducing to a considerable extent the tendency of the X-ray tube **10** to overheat. By controlling the D.C. current applied to the D.C. control winding **83** of the saturable reactor **81** in the present apparatus, voltage is applied to the primary **33** of the high tension transformer **31** during a maximum period GH, as shown in Fig. 3, or during a minimum period KH, as shown in Fig. 3. Thus, by automatic control of the saturable reactor **81** in response to changes in brightness of the image appearing at the fluorescent screen member **47**, the X-ray tube voltage control brightness stabilizer circuit **71** introduces a smaller or greater delay in the instant of firing of the thyratron contactor **101**, thereby varying the voltage applied to the primary **33** of the high tension transformer **31**, and consequently varying the voltage applied to the X-ray tube **10** through the high voltage rectifier circuit **29** so as to assist in stabilizing the brightness of the visible image at the screen member **47**.

Fig. 4 shows a wave-shaped diagram of the voltage appearing across the X-ray tube **10** of the apparatus when the X-ray tube **10** is conducting approximately 20 milliamperes of anode current. In Fig. 4, curve **150** represents the wave shape appearing at the output of a conventional full-wave rectifier, and is provided as a reference wave shape. Curve **153** represents the voltage wave shape appearing across the X-ray tube **10** when power is applied to transformer **31** through a mechanical contactor. Curves **155** are oscillographic representations of the voltage appearing across the X-ray tube **10** when the conduction of the thyratrons **103** and **111** is initiated at the 90° point of the thyratron tube anode voltage wave. The differential between waves **153** and **155** is represented by **157** and results from the fixed anode to cathode voltage drop inherent in discharge devices **103** and **111**.

If the phase shifting network **89** were arranged to vary the ignition time of each thyratron across a time range FG, Fig. 3, from the 0° point to the 90° point of the anode voltage wave, the peak voltage amplitude applied to the X-ray tube **10** would be varied through only a negligible amount, less than the differential **157** shown in Fig. 4. In contrast, the stabilizer circuit **71** of this invention is preferably arranged to vary the ignition point of each thyratron **103** and **111** across a range GK from approximately the 90° point to approximately the 150° point of its respective anode to cathode voltage wave. By providing that unusual range GK of ignition point control, the voltage applied to the X-ray tube **10** is controlled from a maximum as shown by curve **155** to a minimum voltage which results from conduction period KH. Thus it is seen that the particular range GK of ignition point control provides a maximum variation in the voltage **155** applied to the X-ray tube **10** in response to a smaller variation in input signal than would otherwise be required. A given incremental change in brightness of the image at screen member **47** is, therefore, accompanied by a larger change in X-ray tube voltage than would be the case if the ignition point were shifted within the range FG.

During a typical medical examination the body tissue and internal organs that are being scanned by the image intensifier **43** may have widely variable absorption characteristics. In addition, barium sulphate, which is often ingested by a patient for the purpose of gastro-intestinal examinations is so X-ray opaque that various portions of the areas scanned may be almost entirely opaque to the X-ray beam. Under such conditions the visible image at the fluorescent screen member **47** will be subject to sudden changes from low brightness to high brightness as the image intensifier **43** and the X-ray tube **10** are moved with respect to the patient **57**. Under these conditions of rapidly and erratically changing image brightness, any manual system of brightness control or film density control would be clearly impractical. Likewise, the manual control of voltage applied to the X-ray tube **10** alone would be helpful but not entirely adequate for maintaining optimum brightness and optimum contrast. The control of X-ray tube anode current as by means of a current control brightness stabilzer circuit **132** alone would similarly be inadequate to maintain optimum image brightness and optimum image contrast.

In the present apparatus, as the absorption characteristics of the object scanned suddenly change from a minimum absorption to a maximum absorption, the photosensitive member **49** will instantaneously and dynamically detect incremental changes in image brightness and will impose a first signal voltage component **54** on the current control brightness stabilizer circuit **132** and a second signal voltage component **55** on the X-ray tube voltage control brightness stabilizer circuit **71**. The current control brightness stabilizer circuit **132** will increase the electron emission of the X-ray tube filament **12** to thereby increase the intensity of the X-ray beam with an accompanying stabilization of the brightness of the image at the fluorescent screen member **47**. Simultaneously, the X-ray tube voltage stabilizer circuit **71** will shift the phase of the alternating current control voltages applied to the control grid 105 of the first thyratron tube 103 and the control grid 113 of the second thyratron tube 111 so that the thyratron tubes will conduct during a greater portion of the applied anode voltage wave and will thereby impress a higher energizing voltage on the primary 33 of the high tension transformer 31 during a greater portion of the cyclical period of energization of the X-ray tube 10 with an accompanying increase in the voltage applied to the X-ray tube 10.

When a relatively thin or relatively ray transparent portion of the object scanned is interposed between the X-ray tube 10 and the image intensifier 43, the X-ray tube voltage brightness stabilizer circuit 71 will automatically adjust the phase of the control voltage applied to the thyratron grids 105 and 113. The said control voltages are immediately caused to lag the alternating current voltage applied to the thyratron anodes 109 and 117 by approximately 150°, thereby permitting the thyratrons to conduct only during approximately the last 30 electrical degrees of each successive half cycle of applied anode voltage. The voltage applied to the X-ray tube anode 11 will be less than one half of the maximum voltage which would be applied to the X-ray tube anode if the thyratrons were allowed to conduct during the whole of each successive half cycle.

Thus, it is seen that the apparatus, including the X-ray generator, the image intensifier tube 43, the photoresponsive means 49, the brightness preamplifier circuit 53, and the current and voltage brightness stabilizer circuits 132 and 71, is operative to simultaneously regulate both the anode current conducted by the X-ray tube 10 and the anode voltage applied to the X-ray tube to cooperatively stabilize the brightness of the light image appearing at the fluorescent screen member 47 in response to changes in the opacity of the object portion scanned by the X-ray beam.

A principal beneficial result obtained by the brightness stabilization system is to maintain the visible image at the fluorescent screen member 47 substantially constant so as to facilitate undisturbed viewing by the diagnostician and to maintain the density of films exposed in the motion picture camera 59 substantially constant, thereby avoiding underexposed or overexposed film frames. A further important result realized by the stabilization apparatus is that the integral of the X-radiation impinging upon the patient over any selected period of time is dynamically maintained at the absolute minimum commensurate with adequate photographic results. Thus it is possible to cinefluorograph a single patient for longer periods of time to obtain longer sequences of motion picture than would be possible with any other known X-ray apparatus.

By proper selection of component values, the electronic contactor 101 is smoothly controlled to initiate conduction at points ranging from approximately the 90° point of each half cycle. The fractional portion of each half cycle during which the thyratrons 103 and 111 conduct is dependent on the brightness of the image at the fluorescent screen 47 and is inversely responsive to incremental changes in the brightness of the visible image. Thus, the peak kilovoltage applied to the X-ray tube 10 by means of the high tension rectifier unit 29 is varied in response to changes in brightness at the fluorescent screen member 47 so that light intensity at the camera focal plane is maintained substantially constant at a brightness level commensurate with optimum photographic efficiency.

As indicated by Figs. 3 and 4, it has been found that the voltage developed across the X-ray tube by the high voltage circuit is not a direct function of the R.M.S. voltage or the average voltage applied to the primary winding 33 of the high tension transformer 31. Rather, the peak kilovoltage applied to the X-ray tube 10 is dependent on the peak voltage applied to the primary winding 33. Thus, controlling the electronic contactor 101 so as to initiate conduction at different points between the beginning and the 90° points of each half cycle of the voltage source wave would not have an appreciable effect on the peak voltage applied to the transformer primary winding 33 and hence the kilovoltage applied to the X-ray tube 10 would not be satisfactorily responsive to phase shifting of the ignition point of the thyratrons 103 and 111. In contrast, the voltage control brightness stabilizer circuit of my invention controls the electronic contactor 101 so as to cause conduction of the respective thyratron tubes at phase angles between the 90° point of each half cycle and the 150° point of each half cycle of the voltage source wave form, thereby providing smooth continuous variability of the X-ray tube anode to cathode potential in response to changes in the brightness of the image at the fluorescent screen member 47.

The light responsive member 49 or photoelectric means in a preferred embodiment of the invention comprises a photomultiplier tube having a plurality of dynodes, a cathode and an anode, and being responsive to visible light such as that emanating from the fluorescent screen member 47 to produce a direct current electrical signal which is proportional to the brightness of the visible light image. The phototube power supply 51 for the photomultiplier tube 47 may be any conventional source of regulated high voltage direct current power. Such regulated voltage supply sources are well known in the art. The image tube power supply 45 is a D.C. voltage source capable of energizing the image intensifier tube 43 at a voltage of about 30,000 volts and capable of delivering a load current of about 2 milliamperes. Any of various well-known D.C. power supplies meeting the stated specifications may be used to supply power to the image intensifier tube 43.

Although we have shown and described certain specific embodiments of the present invention, it should be apparent to those skilled in the art that the invention is not limited to the specific embodiments described, but that many modifications thereof may be made. For example, the image intensifier tube may not be desired and may not be necessary in a specific embodiment, and instead of the X-ray responsive visible image producing member 47 may include an X-ray sensitive phosphor or like material which is directly responsive to X-rays from the X-ray tube 10 to produce a visible light image.

I claim as my invention:

1. In X-ray apparatus including an X-ray tube having an anode and a filament and operable to project an X-ray beam through an object, the combination of a fluorescent member operable to produce a visible image, photoelectric means associated with said member and responsive to the brightness of said visible image, a source of electrical energy for heating the filament of said X-ray tube, an excitation circuit for supplying current to the anode of said X-ray tube, said circuit including a contactor connected to control excitation of said X-ray tube, a first image brightness stabilizer circuit connected between said photoelectric means and said contactor, a second image brightness stabilizer circuit connected between said source of heating energy and said filament, with both said stabilizer circuits being responsive to said photoelectric means to maintain the brightness of said image substantially constant.

2. In an X-ray apparatus including an X-ray tube having a filament to be heated and further including a fluorescent member to produce a visible image, the combination of an excitation circuit for said X-ray tube including a high tension transformer and an electronic contactor connected between said transformer and a source of supply voltage, a phase shift circuit connected to said contactor to control the cyclical time period of conduction thereof, said phase shift circuit including a variable impedance member responsive to imposition of a control voltage component thereupon, a source of electrical energy for heating the filament of said X-ray tube, induc-

tive means connected between said filament and said source of heating energy and operable upon the imposition of a control current thereupon to control the flow of heating current to said filament, photoelectric means associated with said fluorescent member and operative to produce an electrical output signal proportional to the brightness of said image, and circuit means connected to said phase shift circuit to impose a control voltage component on said variable impedance in response to a change in said electrical output signal, said circuit means being also connected to said inductive means and operable in response to a change in said electrical output signal to cause the imposition of a control current component upon said inductive means.

3. In an X-ray apparatus, an X-ray tube having an anode and having a filament to be heated and operable to project an X-ray beam through an object, a fluorescent member operable to produce a visible image of said object, photoelectric means associated with said fluorescent means and operable to provide an electrical current proportional to the brightness of said visible image, a source of electrical energy for heating the filament of said X-ray tube, inductive means connected with said source of heating energy to control the flow of heating current to said filament, an excitation circuit for said X-ray tube including a high tension transformer having its primary winding connected through an electronic contactor to a source of alternating current supply voltage and having its secondary connected to supply current to said X-ray tube anode, first circuit means responsively associated with said photoelectric means and connected to said contactor to cause a variation in cyclical time period of conductivity of said contactor, and second circuit means responsively associated with said photoelectric means and connected to said inductive means to cause the imposition of a control current component upon said inductive means accompanied by a variation in the heating current supplied to the filament of said X-ray tube, with both said variation in heating current and said variation in cyclical time period being in inverse relation to variations in brightness of said image whereby said brightness is maintained substantially constant regardless of variations in the density of said object.

4. In X-ray apparatus including an X-ray tube provided with a filament to be heated and a fluorescent member for producing a visible image, the combination of a voltage supply for said X-ray tube including a high tension transformer having its secondary winding connected in circuit with said X-ray tube for supplying unidirectional current thereto and having its primary winding connected through an electronic contactor including a pair of inverse-parallel connected discharge devices to a source of alternating current supply voltage, an image brightness responsive means associated with said fluorescent member for producing a signal voltage proportional to the brightness of said visible image, a first image brightness stabilizer circuit including a saturable reactor operatively connected with said X-ray tube filament and with a source of filament heating current and operable upon the imposition of a direct current component thereon to control the flow of heating current to the cathode of said X-ray tube, a second image brightness stabilizer circuit including a phase shifting network connected to said pair of inverse-parallel connected discharge devices, with said second stabilizer circuit being operable upon the imposition of a control signal thereupon, to control the cyclical time period of conduction of said discharge devices, and circuit means connected between each of said first and second image brightness stabilizer circuits and said image brightness responsive means to cause the imposition of control signal current components upon said first and second stabilizer circuits in response to said signal voltage accompanied by a variation in the heating current supplied to the filament of said X-ray tube and further accompanied by a variation in cyclical time period of conduction of said discharge devices, said variations being inversely responsive to variations in the brightness of said visible image, whereby the brightness of said visible image is maintained substantially constant.

5. In X-ray apparatus including an X-ray generator and a fluorescent member for producing a visible image, the combination of a photoelectric means associated with said fluorescent member and responsive to the brightness of said image, an electronic contactor, a voltage supply circuit connected through said electronic contactor to said X-ray generator, and an image brightness stabilizer circuit connected between said photoelectric member and said electronic contactor to control the cyclical time period of conduction thereof.

6. In X-ray apparatus including an X-ray generator and a fluorescent member for producing a visible image, the combination of a photoelectric member associated with said fluorescent member and responsive to the brightness of said image, an electronic contactor, a voltage supply circuit connected through said electronic contactor to said X-ray generator, and an image brightness stabilizer circuit including a phase shift network connected between said photoelectric member and said electronic contactor and operative to control the conductivity of said contactor in response to the brightness of said image.

7. In X-ray apparatus including an X-ray generator and a fluorescent member for producing a visible image, the combination of a photoelectric means associated with said fluorescent member and responsive to the brightness of said image, an electronic contactor, voltage supply means connected through said electronic contactor to said X-ray generator, and an image brightness stabilizer circuit connected between said photoelectric member and said electronic contactor, with said stabilizer circuit being connected so that a variation in the brightness of said image causes the imposition of a voltage component upon said contactor accompanied by a variation in the period of conductivity of said contactor inversely to the said variation in the brightness of said image.

8. In an X-ray apparatus including an X-ray generator, a fluorescent member to produce a visible image, and a photosensitive device having an output signal proportional to the brightness of said image, the combination of an electronic contactor connected so as to energize said X-ray generator, a phase shift circuit connected to said contactor to control the period of conductivity thereof, said phase shift circuit including a saturable reactor having a direct current control winding and means for passing a current proportional to said output signal through said control winding.

9. In combination, an X-ray tube, an energizing circuit for successively energizing said X-ray tube, an image intensifier embodying an electron image of an object irradiated by said source and operative to provide a visible light image of said object, a light responsive member associated with said image intensifier and having an output voltage proportional to the brightness of said image, photographic apparatus for cyclically recording successive latent images of said light image, and an image brightness stabilizer circuit connected between said light-responsive member and said energizing circuit, said stabilizer circuit being operative to variably control the duration and intensity of each period of energization of said X-ray tube by said energizing circuit, whereby the density of said latent images are maintained substantially constant.

10. In X-ray apparatus including an X-ray generator and a commercial source of alternating current voltage for energizing said generator, the combination of a fluorescent image-forming member, a photoelectric member associated with said image-forming member, an electronic contactor including a pair of inverse-parallel connected unilaterally conductive devices connected between said source and said generator, and a brightness stabilizer circuit including a phase-shifting network, with said con-

tactor being connected to said phase-shifting network to be responsive thereto and with said stabilizer circuit being connected to said photoelectric member to change the average conductivity of said contactor in inverse response to changes in brightness of said image.

11. In X-ray apparatus including a fluorescent member operable to produce a visible image, an X-ray generator for projecting an X-ray beam through an object to said fluorescent member and further including an electronic contactor for energizing said X-ray generator, the combination of a light responsive member positioned relative to said fluorescent member to be responsive to the brightness of said visible image and an image brightness stabilizer circuit connected between said contactor and said light-responsive member, with said circuit including a phase-shifting network connected to a control element of said contactor and being operative to permit conduction by said contactor during less than 90 electrical degrees of each successive half cycle of an applied A.C. voltage wave.

12. An X-ray generator for projecting an X-ray beam through an object, a fluorescent member operable to intercept said beam and to produce a visible image, a photosensitive member having an electrical output signal proportional to the brightness of said image, an electronic contactor for said generator including a pair of inverse-parallel connected discharge devices each having a control electrode, and an image brightness stabilizer circuit connected between said photosensitive member and at least one of said control electrodes to vary the cyclic period of conductivity of said contactor in response to the brightness of said visible image.

13. The apparatus of claim 12 wherein said stabilizer circuit comprises a phase-shifting circuit, an alternating current voltage supply source, and a transformer having a primary connected in series with said phase-shifting circuit and said A.C. voltage supply source, said transformer having a secondary winding connected in circuit with the control electrode of one of said discharge devices.

14. In X-ray apparatus including an X-ray tube and a fluorescent screen for producing a visible image, the combination of a voltage supply circuit for said X-ray tube including a high tension transformer having its secondary winding connected through a rectifying arrangement to said X-ray tube and having its primary winding connected through an electronic contactor to an alternating current supply source, a light-responsive member positioned relative to said fluorescent screen to be responsive to the brightness of said image and having an electrical output signal proportional to said brightness, a phase-shifting circuit including a variable impedance device associated with said electronic contactor and operable upon the imposition of a control signal current component thereupon to change the cyclical period of conductivity of said contactor, and means connected to said light-responsive member and responsive to variations in said electrical output signal to cause the imposition of a current component upon said impedance device accompanied by a variation in the cyclical period of conductivity of said contactor.

15. In X-ray apparatus including an X-ray tube and a fluorescent screen for producing a visible image, the combination of a voltage supply circuit for said X-ray tube including a high tension transformer having its secondary winding connected through a rectifying arrangement to said X-ray tube and having its primary winding connected through an electronic contactor to an alternating current supply source, with said contactor having a cyclical period of conductivity of variable time duration, a light responsive member positioned relative to said fluorescent screen to be responsive to the brightness of said image and having an electrical output signal proportional to said brightness, a phase-shifting circuit including a variable impedance device associated with said electronic contactor and operable upon the imposition of a control signal current component thereupon to change the cyclical period of conductivity of said contactor, and means connected to said light-responsive member and responsive to variations in said electrical output signal to cause the imposition of a current component upon said impedance device accompanied by a variation in the cyclical period of conductivity of said contactor.

16. Cinefluorographic X-ray apparatus comprising an X-ray tube having an anode, cathode and filament, X-ray-responsive means for producing a luminous image, motion picture camera means for recording on film said luminous image, first circuit means for controlling supply of current to said filament, second circuit means for controlling the voltage applied across said anode and cathode, and means responsive to the degree of brightness of said luminous image for controlling the aforesaid first and second circuit means to maintain said degree of brightness substantially constant.

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