A system for controlling the filament power applied to a rotating anode X-ray tube when used with a three phase generator. A square-wave drive signal is applied to the filament from an inverter synchronously operated in accordance with the 60Hz power line. The amplitude of the square-wave output from the inverter is varied in response to the operation of a series regulator selectively controlled by the composite output of a summing amplifier having inputs corresponding to filament current, desired MA, and space charge compensation prior to excitation of the X-ray tube but only to the actual MA compared against a reference potential during excitation.
FIG. 3a
FIG. 5

Filament Voltage (Prior Art)

f = 60 Hz

FIG. 6

Filament Voltage (Prior Art)

FIG. 7

Filament Voltage

V^2

V

V^2

V
FILAMENT CURRENT REGULATOR FOR ROTATING ANODE X-RAY TUBES

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to X-ray apparatus and more particularly to a system which is adapted to eliminate excessive ripple in the KV waveform of a three phase generator used in connection with a rotating anode X-ray tube.

2. Description of the Prior Art


It has been observed, however, that when a three phase generator including a high voltage transformer and full wave rectifier is coupled across the anode and filament of an X-ray tube, KV ripple is seriously affected by the type of filament drive employed particularly when operating with X-ray tube currents in the region of 1,000 milliamperes (ma) or above. Tests conducted utilizing pure sine-waves, sine-waves whose conduction angle is controlled, direct current and square waves for driving the filament indicate that the KV waveform ripple content was excessive for both types of sine-wave drive while being substantially reduced and/or eliminated with a DC or a square-wave drive. Inasmuch as it has been found to be impractical to use direct current for driving the filament of an X-ray tube, the present invention contemplates the use of a controlled square-wave drive for overcoming the aforementioned ripple problem.

SUMMARY

Briefly, the subject invention is directed to the concept of supplying the filament of an X-ray tube by means of a square wave signal voltage generated by an inverter circuit operated in accordance with the output from a bistable circuit which in turn is controlled by a zero cross-over detector circuit responsive to the 60Hz power line voltage. The output of the inverter, moreover, is controlled by means of a series regulator operated in accordance with the output of a summing amplifier selectively having applied thereto signals corresponding to the actual filament current, actual MA, desired or "preset" MA, and space charge compensation. An exposure gate circuit, moreover, is included whereby the aforementioned filament current, preset MA and space charge compensation signals are summed together at the input of a summing amplifier prior to an X-ray exposure but wherein only a signal corresponding to the actual MA signal compared against a fixed reference is applied to the summing amplifier during an actual exposure. Additionally, protective circuitry is also included which if the filament current is too high for the filament (spot size) utilized causes a circuit breaker to trip, deactivating the inverter through the series regulator and thereby removing the filament drive from the X-ray tube.
whose primary winding 50 includes a center tap 52 which is connected to the output of a series type regulator circuit 54. The end terminals of the primary winding 50 are connected to a DC to AC inverter circuit 56 which includes suitable driver circuits which are operated in accordance with the square-wave outputs of a binary divide by two (+2) flip-flop circuit 58. The flip-flop circuit 58 in turn is driven by the output of a pulse shaper 60 which is adapted to provide suitable trigger pulses at a 120Hz rate in accordance with the output of a zero cross-over detector 62. The cross-over detector 62 is coupled to the 60Hz power line through the secondary winding 64 of a transformer 66 whose primary winding is coupled to a single phase 60Hz power line.

The series regulator 54 is adapted to control the amplitude of the square-wave output from the inverter 56 as it appears across the secondary winding 51 of the output transformer 48 in accordance with the output of a summing amplifier 68 whose input prior to X-ray tube excitation is connected to a voltage summing point 70 by means of a first but normally closed electrically operated switch device 72 which connects to circuit junction 69. During actual exposure, however, the switch 72 is opened and a second but normally open switch 74 is closed coupling a voltage indicative of the actual MA to the circuit junction 69. Operation of the switches 72 and 74 is provided by an exposure gate control circuit 76 whose input is responsive to the voltage across "drop wire resistor" 42. The voltage summing point 70 is adapted to continuously receive three signal voltage corresponding, respectively, to the RMS value of the filament current, the desired or preset MA, and space charge compensation. The latter signal is a function of both the desired MA and selected high voltage or KV.

The signal voltage proportional to the RMS value of the filament current is provided by a filament current sensor circuit 78 which is coupled to the secondary winding 79 of a transformer 80 whose primary winding 81 is coupled in series to ground with the secondary winding 51 of the inverter output transformer 48. The MA, preset, or voltage proportional to the desired MA is provided by means of a resistance voltage divider circuit provided by a variable resistor 82 connected in series to a fixed resistor 84. The upper end terminal of the variable resistor 82 is connected to a reference potential of positive polarity while the lower end of the fixed resistor 84 is connected to ground. The common connection 85 between resistances 82 and 84 is connected to the summing point 70. The space charge compensation signal voltage is provided by a space charge function generator 86 having a variable resistor 88 coupled thereto whose value is proportional to the desired MA as well as a voltage input proportional to desired KV which as noted above is the high voltage used to excite the X-ray tube 10 from the three-phase generator 16. This signal is provided by a digital to analog converter 90 which receives a digital word from a KV select keyboard and logic section 92. The signal voltage corresponding to actual MA applied to junction 69 during X-ray exposure, however, constitutes an error signal derived from the comparison of the voltage across the dropwire resistor 42 and a negative polarity reference voltage applied to a comparator amplifier 94 at terminal 95.

The series regulator 54 while being controlled by the output of the summing amplifier 68 is adapted to be operated only when a supply voltage (+24V) applied to terminal 96 is coupled thereto through a circuit breaker 98 and a control voltage is applied to terminal 100. The control voltage applied to terminal 100 comprises a "boost command" signal from one of two switches, not shown, which must be closed sequentially in order to make an X-ray exposure. The boost command switch is actuated just prior (1.0 second or more) to the operation of the X-ray exposure switch in order to bring the rotating anode 14 up to speed and to bring the filament 12 up to temperature before applying the high voltage.

The circuit breaker 98, however, is adapted to be tripped, i.e. opened, by means of the solenoid 102 which in turn is adapted to be energized by means of a filament current protection circuit 104. The current protection circuit 104 is coupled to a filament spot size selection circuit 106 since the tube 10 actually includes at least two filaments for different focal spot sizes and a current limit selection circuit 108. Circuit 104 is adapted to compare the actual filament current from the sensor circuit 78 with a signal from 108 corresponding to the maximum allowable current for a selected filament and thus prevent inadvertent damage to the X-ray tube 10.

Considering now the invention in greater detail, reference is made to a schematic diagram of the preferred embodiment as illustrated in FIGS. 3a and 3b. The single phase 60Hz line voltage appearing across the secondary winding 64 of the transformer 66 as shown in FIG. 2, is applied to terminals 110 and 112. Since the center tap of the secondary winding 64 is grounded, the line voltage appearing at terminals 110 and 112 are mutually 180° out of phase with respect to one another. Terminals 110 and 112 are coupled to a common junction point 114 by means of the half-wave rectifier semiconductor diodes 116 and 118. Connected between junction 114 and ground is a transient suppressor 120 comprised of a metal oxide varistor well known in the art. The zero cross-over detector 62 is coupled between junction 114 and ground by means of a resistor 122. The zero cross-over detector 62 is comprised of a light emitting diode 124 which is optically coupled to a Darlington transistor circuit including a photo transistor 126 and transistor 127. As 60Hz line voltage is applied, the signal appearing at circuit junction 128 constitutes pulses having a frequency of 120Hz. These pulse signals are next fed to the pulse shaper 60 which comprises a signal amplifier which is adapted to provide substantially square-wave output pulses having respective pulse widths in the order of 200 microseconds in relation to the 8.3 millisecond period. The 120Hz pulse train output from the pulse shaper 60 is fed to the C input of flip-flop circuit 58 which constitutes a flip-flop. It acts as a divide by two (+2) binary counter providing 60Hz complementary square-wave outputs at the Q and Q output terminals. The 60Hz square wave from the Q output of the flip-flop 58 is fed to first driver amplifier comprising transistor 130 whose collector electrode is coupled to the base of transistor 132 forming one half of the inverter circuit 56. In a similar manner, the Q output from the flip-flop 58 is coupled to a second driver comprising transistor 134 which is adapted to be coupled to the base of transistor 136 in the other half of the inverter 56. The emitters of transistors 132 and 136 are returned to ground through a common resistor 138 while their respective collectors
are coupled to opposite ends of the primary winding 50 of the output transformer 48. The collector supply voltage for the transistors 132 and 136 in the inverter is applied through the primary winding's center tap 52 which is connected back to a positive supply potential (+24V) applied to terminal 96 through the circuit breaker 98 and transistor 140 in the series regulator 54. Whereas the respective square-wave signals applied to the base of transistors 132 and 136 comprise unipolar complementary square-waves separated in time by a half a period, the inverter circuit 56 operates to provide a bi-polar square-wave as shown by FIG. 7 on the secondary winding 51 of transformer 48 which bi-polar square-wave signal is fed to the filament 12 of the X-ray tube 10 by means of the filament transformer 46 (FIG. 1).

It is to be noted that the inverter circuit 56 becomes inoperative when either the boost command voltage is absent or upon the opening of the circuit breaker 98 which removes the +24 volts from the center tap 52 of the primary winding 50 of the output transformer 48. The collector-emitter junction of transistor 140 of the series regulator 54 provides a series impedance with the center tap 52 to vary the magnitude of the supply potential applied to the inverter transistors 132 and 134. The series regulator circuit 54 additionally includes transistors 142, 144 and 146. Transistors 142 and 144 operate to render the regulator circuit selectively operative and inoperative while transistor 146 is adapted to control the level of conduction and accordingly the series impedance value exhibited by the transistor 140. The emitter of transistor 144 is coupled to supply voltage (+40V) terminal 148 which is also coupled to the collector of transistor 142 through the Zener diode 150 and resistor 152. When a boost command control signal (+24V) is applied to the base of transistor 142, transistor 144 is turned on to render inverter circuit 56 to become operative and generate the bi-polar square-wave fed to the X-ray tube filament 12 shown in FIG. 1. The amplitude of the bi-polar square-wave applied to the filament 12, however, is determined by the voltage applied to the base of transistor 146 from the output of the summing amplifier 68.

The summing amplifier is comprised of an amplifier of known design, having a feedback resistor 154 coupled from the output to its negative input terminal which is also common to circuit junction 69 while the positive input terminal has a feedback voltage applied thereto by means of fixed resistors 156 and 158, and capacitor 162 which resisters and capacitor are coupled to the collector of transistor 146 through capacitor 162. The negative (−) input of the amplifier 68 accordingly constitutes the signal input and is adapted to receive the algebraic summation or composite of the desired (preset) MA signal, the RMS value of the filament current signal, and the space charge compensation signal prior to exposure while only the signal proportional to the actual MA compared against a reference voltage during the X-ray exposure. This was shown to be accomplished by means of the normally closed switch 72 and the normally open switch 74 shown in FIG. 1. These switches in actuality comprise field effect transistor (FET) switches wherein the drain and source of FET switch 72 respectively are connected between circuit junction 69 and the summing point 70. The drain of FET switch 74 is connected to circuit junction 69 while the source is connected to the output of the error amplifier 94 used to compare the actual MA signal appearing across resistance 42 (FIG. 1) and the reference voltage (−15V) applied to terminal 95. The gate of FET switch 74 is connected to the collector of transistor 162 which forms part of the gate control circuit 76 while the gate of FET switch 74 is connected by means of junction 165 to the collector of transistor 166 which is also part of the gate control circuit 76 as well as the base of transistor 164. The gate control circuit 76 is additionally comprised of a timer circuit 168, amplifier 170, and transistors 172, 174 and 176.

In the configuration shown, FET switch 72 is normally conductive such that prior to excitation of the X-ray tube 10, the summing point 70 is directly connected to circuit junction 69 which is also common to the input to the summing amplifier 68. During an actual exposure, however, FET switch 72 is rendered non-conductive, disconnecting summing point 70 from the summing amplifier input; however, FET switch 74 is rendered conductive, thereby coupling the output of the error amplifier 94 to circuit junction 69. This is accomplished in the following manner. Transistor 166 is biased such that it is normally non-conductive bringing circuit junction 165 substantially to +24V. Since junction 165 is coupled to the base of transistor 164 through resistor 178, this transistor is conductive. Accordingly, the gate of FET switch 72 has the negative supply potential (−15V) applied thereto, rendering it conductive, whereas the gate of FET switch 74 being at +24V, remains non-conductive. Upon the excitation of the X-ray tube 10 by the high voltage generator 16 (FIG. 1), a negative polarity voltage proportional to the actual MA appearing across the variable resistor 42 shown in FIG. 1, appears at terminal 180. This voltage is coupled to the positive (+) input of amplifier 94 by means of resistor 179 which is also common to circuit junction 182. A transient suppressor 181 and a pair of Zener diodes are also coupled to ground on either side of resistor 179. The MA signal appearing at circuit junction 182 is coupled to pin 2 of the timer 168 by means of amplifier 170 and transistor 172 which triggers the timer 168 whereinupon a signal appears at pin 1. The timer output signal is coupled to the emitter of transistor 174, which operates to render transistor 166 conductive, thereby causing circuit junction 165 to fall to the negative supply potential, i.e. −15V. This then causes FET switch 74 to become conductive, coupling the output of the error amplifier 94 to the input of the summing amplifier 68. At the same time, transistor 164 becomes non-conductive, rendering FET switch 72 non-conductive, thereby disconnecting the summing point 70 from circuit junction 69.

When the timer circuit 168 is triggered upon the X-ray tube excitation, an external visual type EXPOSURE indicator 184 e.g. an indicator light is also energized. After a predetermined time delay determined by the circuit elements shown generally by reference numeral 186, the timer again reverts back to its normal state and an END OF EXPOSURE indicator 188 connected to pin 13 is energized. Considering the purpose of transistor 176 shown coupled to transistor 174, it has its base connected to terminal 190 which is adapted to receive an input type control signal provided during a system calibrate procedure wherein the system presets which constitutes, for example, the variable resist-
tors 82 and 88 shown in FIG. 1 and located in the calibrat
ror module 44 are set prior to making an X-ray ex-
posure. Transistor 176 thereby inhibits any change from the normal operating states of FET switches 72 and 74, except during actual X-ray tube excitation.

The actual MA signal applied to the error amplifier 94 from terminal 180 has a negative reference voltage (−15 V) applied to its negative input terminal by means of terminal 192 and a fixed resistor 214. This voltage 94 itself consists of a comparator or error amplifier having a feedback resistor 196 coupled between the output and the negative input terminal. Thus the output voltage of the error amplifier 94 comprises the error or difference voltage between the reference voltage and the voltage appearing at terminal 180. This error signal is coupled to circuit junction 69 by means of resistor 197.

Considering now in greater detail the circuitry supplying the three operational signal inputs to the summing point 70, which as noted before, comprises the desired or preset MA signal, the signal corresponding to the RMS value of the filament current, and the space charge compensation signal, the voltage proportional to the preset MA which appears at junction 85 shown in FIG. 1, is provided by coupling the variable resistor 82 to terminal 198. A summing resistor 200 is connected between circuit junction 85 and the summing point 70. A capacitor 202 is coupled between terminal 198 and ground to provide a desired filtering effect. The voltage corresponding to the RMS value of the actual filament current is coupled to summing point 70 by means of the summing resistor 204. This signal voltage is developed by the filament current sense circuit 78 which includes an integrator consisting of an operational amplifier 206 having feedback means 208 and whose negative input is connected to the DC output of a semiconductor diode bridge rectifier 210 coupled to the secondary winding 79 of the transformer 80. A transient suppressor 212 is also connected across the secondary winding 79. Regarding the space charge compensation signal voltage, it is coupled to summing point 70 by means of summing resistor 200. This voltage is developed by the space charge function generator circuit 86 shown in FIG. 1. This circuit, however, is comprised of a pair of series connected operational amplifiers 216 and 218, whose output is connected to one input (+) of amplifier 220. The negative (−) and positive (+) inputs of amplifier 216 are respectively coupled to terminals 222 and 224 across which an analog voltage proportional to the selected KV is applied from the digital to analog converter 90 shown in FIG. 1. This voltage is amplified and applied to the negative input terminal of amplifier 220 by means of the resistor 226. The negative input terminal of amplifier 220 also has a negative reference potential (−15 V) connected to terminal 228. This reference voltage is coupled thereto by means of the fixed resistors 230 and 232, whose common connection is connected to a Zener diode 234. Additionally, across the negative input terminal and output terminal of amplifier 220, is connected a pair of circuit terminals 236 and 238 to which is coupled the variable resistance 88 shown in FIG. 1, which is also proportional to desired MA.

Referring now to the filament current protection circuit 104 of FIG. 1 in greater detail, it consists of an amplifier 240 coupled to the output of the integrator amplifier 208 included in a filament current sensor circuit.
set limit as established by the potentiometers 252 and 254, depending upon the spot size selected, the filament protection circuit 104 will activate the circuit breaker 98, causing the inverter circuit 56 to become inoperative and thus remove all filament voltage from the X-ray tube. Thus what has been shown and described is a square-wave filament drive circuit and regulator therefor which is particularly adapted for use with a three-phase high voltage generator for a rotating anode X-ray tube. The advantage of the square-wave drive immediately becomes evident with reference to FIGS. 4 through 7, inclusive. FIG. 4, for example, illustrates the power variation for a sine-wave filament voltage drive. Curve 258, for example, is illustrative of a sine-wave of filament voltage at a line frequency of 60Hz. Since power is proportional to the square of the voltage, curve 260 depicts the power variation with time and thus contains a ripple varying at a 120Hz rate. Even where a discontinuous sine-wave of voltage such as shown in FIG. 5 and denoted by curve 262 is applied for example, by means of a triac or other apparatus, the power curve 264 still exhibits a 120Hz variation which can be readily observed and has been found to be objectionable for a three-phase generator system. FIG. 6 discloses that with a direct current applied to the filament, the power variation 265 is constant with respect to time, thus exhibiting none of the objectionable ripple referred to. However, as already noted, it has been found to be impractical to use DC on the filament of an X-ray tube. The same ripple free effect nevertheless can be obtained by use of a square-wave drive such as shown in FIG. 7 wherein curve 266 corresponds to the filament drive appearing at the output or secondary winding 51 of the inverter output transformer 48 and wherein curve 268 denotes the power variation with time. Thus precise and adequate control of filament current of an X-ray tube is maintained in an improved manner by the embodiment set forth in the foregoing specification.

Accordingly, we claim as our invention:
1. A system for controlling the filament power applied to an X-ray tube having at least one filament and an anode, comprising in combination:
a square-wave filament drive circuit, including means operated in synchronism with the power line feeding the X-ray tube, coupled to said filament and providing a controlled square-wave signal of variable amplitude thereto for powering said at least one filament;
control circuit means coupled to said drive circuit providing a signal for controlling the amplitude of said square-wave, said control circuit means including means for being selectively enabled and operated in response to a first input signal coupled thereto prior to excitation of said X-ray tube wherein X-rays are generated thereby and to a second input signal coupled thereto after initiation of excitation of said X-ray tube;
first circuit means including a signal summing point coupled to and being responsive to signals representative of a desired anode current, space charge compensation, and the filament current flowing in said filament and providing a composite signal thereby, said composite signal being said first input signal; and
second circuit means including error signal generator means coupled to signals respectively representative of the actual anode current and a predetermined reference signal and being operable to provide an error signal output, said error signal being said second input signal.
2. The system as defined by claim 1 wherein said filament drive circuit includes an inverter circuit.
3. The system as defined by claim 2 wherein said drive circuit additionally includes signal generator means responsive to a power line frequency potential and providing a pulse train having a frequency twice the power line frequency;
a binary circuit coupled to said pulse train providing a pair of complementary square-wave output signals coupled to said inverter circuit for operating said inverter circuit in synchronism with and at the power line frequency.
4. The system as defined by claim 3 wherein said signal generator means comprises a zero cross-over detector circuit, and
wherein said binary circuit comprises a flip-flop circuit.
5. The system as defined by claim 4 wherein said inverter circuit includes an output circuit including means coupled to said control circuit.
6. The system as defined by claim 5 wherein said output circuit includes an output transformer having primary winding including a center tap and a secondary winding, and
wherein said control circuit is coupled to said center tap of said primary winding and said secondary winding is coupled to said at least one filament of said X-ray tube for supplying filament power thereto.
7. The system as defined by claim 6 wherein said control circuit means comprises a series regulator coupled between a supply potential adapted to power said inverter and said center tap of said primary winding.
8. The system as defined by claim 1 wherein said means included in said control circuit means comprises a regulator circuit connected to said filament drive circuit, said regulator circuit additionally including enabling circuit means adapted to receive a command signal for rendering said regulator circuit operable prior to excitation of said X-ray tube, and an input circuit selectively coupled to said first and second input signal for controlling the operation of said regulator circuit.
9. The system as defined by claim 8 wherein said control circuit means additionally includes first switch means adapted to couple said summation point to said input circuit and being normally in a closed circuit condition prior to excitation of said X-ray tube but being in an open circuit condition after initiation of excitation of said X-ray tube, and
second switch means adapted to couple said second circuit means to said input circuit and being normally in an open circuit condition prior to excitation of said X-ray tube but being in a closed circuit condition after initiation of excitation of said X-ray tube.
10. The system as defined by claim 9 wherein said first and second switch means connect to a common circuit junction and additionally including signal amplifier means having input means coupled to said common junction and output means coupled to said input circuit of said regulator means.
11. The system as defined by claim 10 wherein said first and second switch means comprise semiconductor switch means having a pair of signal conducting electrodes and a control electrode and wherein a like signal electrode of each semiconductor switch is coupled to said common junction.

12. The system as defined by claim 11 wherein said first and second semiconductor switch respectively comprises first and second field effect transistors having source, drain, and gate electrodes and wherein the drain electrodes of both transistors are connected to said common junction and wherein the source electrode of said first transistor is connected to said summing point and said source electrode of said second transistor is connected to the output of said error signal generator means.

13. The system as defined by claim 12 wherein said control circuit means additionally includes an exposure gate control circuit coupled to the gate electrodes of said first and second field effect transistor, being operable to provide a gate control signal to said first field effect transistor prior to excitation of said X-ray tube for rendering said transistor conductive while providing a gate control signal to said second field effect transistor to render said transistor non-conductive but upon initiation of excitation of said X-ray tube, coupling a gate control signal to said second field effect transistor for rendering it conductive while coupling a gate control signal to said first field effect transistor for rendering it non-conductive.

14. The system as defined by claim 12 wherein said gate control circuit also includes timer circuit means triggered upon initiation of excitation of said X-ray tube and being operable to initiate the generation of said gate control signals to cause said first and second field effect transistor to switch respective operating states for a predetermined time and thereafter return to their normal operating states.

15. The system as defined by claim 1 and additionally including a filament current sensor circuit providing a signal corresponding to the RMS value of the actual filament current flowing in said at least one filament; circuit means providing a signal indicative of a safe current limit for said at least one filament, and comparator circuit means coupled to said last-mentioned filament current signal and safe current limit signal and providing an output signal rendering said control circuit means and said drive circuit inoperative when the signal corresponding to the actual filament current exceeds a said safe current limit signal.

16. The system as defined by claim 15 wherein said means included in said filament drive circuit includes an inverter circuit which is operable to generate said square-wave signal; and wherein said means included in said control circuit means comprises a series regulator and circuit interrupter means coupled between said inverter circuit and a supply potential, said circuit interrupter means being operable in accordance with said output signal from said comparator to open and disconnect said supply potential from said inverter when the actual filament current exceeds a predetermined safe limit.

17. The system as defined by claim 1 wherein said square-wave filament drive circuit comprises:
   a transformer having a primary winding connected to a power line and a secondary winding;
   a zero cross-over detector coupled to said secondary winding providing output pulses having a frequency twice the power line frequency;
   a pulse shaping circuit coupled to said detector for providing trigger pulses adapted to trigger a multivibrator;
   a bi-stable multivibrator coupled to the output of said pulse shaper and being triggered by the output pulses thereof to provide a first and second complementary square-wave output;
   first and second driver circuit means respectively coupled to said first and second square-wave output, and
   an inverter circuit having first and second inputs respectively coupled to said first and second driver circuit and being alternately driven by said first and second squarewave output and having an output circuit including an output transformer having a primary and secondary winding wherein said secondary winding provides a bi-polar square-wave output signal for powering said at least one filament.

18. The system as defined by claim 17 wherein said zero cross-over detector includes a light emitting diode located within optical coupler means and also including therein photosensitive transistor means optically coupled to said diode and providing output pulse signals at a frequency twice the power line frequency.