(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: **0 151 729**
A2

(12) # EUROPEAN PATENT APPLICATION

(21) Application number: **84114922.2**

(22) Date of filing: **07.12.84**

(51) Int. Cl.4: **H 01 F 19/04**
H 01 F 27/08, H 05 G 1/10

(30) Priority: **22.12.83 US 564602**

(43) Date of publication of application: **21.08.85 Bulletin 85/34**

(84) Designated Contracting States: **DE FR GB NL**

(71) Applicant: **GENERAL ELECTRIC COMPANY**
1 River Road
Schenectady New York 12305(US)

(72) Inventor: **Walker, Paul**
2 Barmeadoy Dobcross Near Saddoeworth
Oldham Lancashire(GB)

(74) Representative: **Schüler, Horst, Dr. European Patent Attorney et al,**
Kaiserstrasse 41
D-6000 Frankfurt/Main 1(DE)

(54) **High-voltage transformer for X-Ray generator.**

(57) A pulse-width-modulated inverter operates with a closely coupled high-voltage transformer and associated filter to provide a voltage output waveform with very fast rise and decay times, a small ripple and very good reproducibility with minimal distortion. This is accomplished with a high-voltage transformer having a very low leakage inductance and distributed capacitance. Evaporative cooling is provided in the transformer tank to accommodate the higher heat losses which are generated by the relatively small transformer operating at relatively high frequencies.

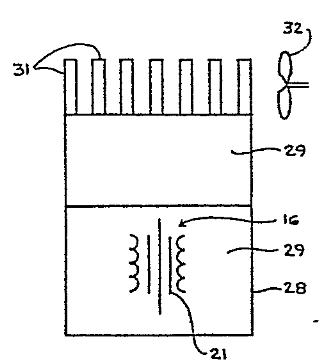

FIG. 3

EP 0 151 729 A2

10374-15XZ-02523
GENERAL ELECTRIC COMPANY

HIGH-VOLTAGE TRANSFORMER FOR X-RAY GENERATOR

Background of the Invention

This invention relates generally to X-ray generator systems and, more particularly, to a high-voltage, high-frequency transformer for application with an inverter in an X-ray generator system.

In the field of X-ray imaging, an X-ray tube is made to produce a stream of X-rays which are directed to penetrate an object to be examined, with the penetrating X-rays being applied to an imaging device for producing an image or density profile of the examined object. The definition and clarity of the resultant image depends not only on the quality of the X-ray tube and the imaging device but also on that of the power supply.

The most common approach for obtaining an exposure for a predetermined period of time is that of pulsing the X-ray tube on for that time period. For that purpose, it is generally desirable that the output from the power supply to the X-ray tube be a square-wave output with a very fast rise and decay time and with very little ripple during the steady-state exposure time period. It is also desirable that the square wave be reproducible with minimal distortion over a wide range of X-ray tube current operation. High reproducibility becomes especially important in dual-energy applications such as may be used in digital subtraction radiography or in computerized tomography.

A typical power supply for an X-ray generator operates at a low frequency (i.e., 50 or 60 Hz) and normally includes an adjustable autotransformer which varies the voltage applied to the step-up transformer. A rectifier converts the high voltage a.c. to d.c. with a low-frequency, high-amplitude ripple. A filter is then applied to smooth the ripple. The resultant output waveform has a relatively slow rise and decay time, a large ripple at steady-state conditions, and poor reproducibility and distortion when used over a wide range of tube currents. The high-voltage transformer which is used with such a system is normally insulated and cooled with mineral oil and is relatively large and heavy (on the order of 350 pounds).

It is known that to improve the wave shape in terms of ripple and its rise and decay times, it is desirable that the transformer frequency be increased. However, an increase in frequency can have undesirable effects in both the core and the coil of the transformer. In the core,,an increase in frequency will cause the hysteresis losses to increase disproportionately more than the frequency to thereby cause a rapid rise in the core temperature. This in turn requires a change of core material and/or an increase in the cooling capacity of the transformer.

In the coil of the transformer, an increase in frequency results in a proportionate increase in the leakage reactance, the distributed capacitance currents, and the skin effect. Each of these properties, in turn, tends to degrade the performance of a transformer in an X-ray generator system. That is, a high-leakage inductance represents a high level of electromagnetic energy that must be overcome and which tends to slow both the rise time and the fall time of the output voltage waveform. The leakage inductance can be especially undesirable in a system having static contactors with associated forced commutation circuitry, which inherently has a high level of leakage inductance.

The distributed capacitance of the high-voltage secondary winding directly affects the reflective peak primary current in light-load conditions (i.e., it causes a large input current and low output voltage during light loading, such as in fluoroscopy) to thereby force the inverter into a current-limiting condition.

The third characteristic which is dependent on frequency is the skin effect, which tends to increase the a.c. resistance of the winding to thereby produce high losses during full-load conditions.

While the above three undesirable conditions are exacerbated by an increase in operating frequency, it is recognized that they can, as well, be reduced by a reduction in the size of the transformer (i.e., a reduction in the cross-sectional area of the magnetic core and in the number of turns in the coil). By reference to the basic transformer equation, one may be inclined to follow an increase in frequency with an associated decrease in the cross-sectional area of the magnetic core and/or the number of turns in the coil. However, one must also recognize that such a reduction in the mass of the transformer also results in an efficiency drop with associated core and copper losses. This, of course, leads to the further generation of heat which, if combined with the heat resulting from the initial raising of the frequency, results in a significant cooling problem. For example, if the current approach of using mineral oil is applied to provide the additional cooling that would be required, the size of the transformer tank would be inordinately large. Further, in the field of X-ray generators, the cooling function has not been accomplished with other than a mineral-oil tank.

In addition to the problem of increased heat, such a reduction in transformer size will also tend to decrease the distance between the layers in the coil to thereby increase the distributed capacitance in the high-voltage windings, a phenomenon which again tends to distort the output waveform, especially at very light loads.

For the above reasons, the concept of using medium or high-frequency power in the transformer of an X-ray generator system has heretofore been precluded.

Objects of the Present Invention

It is therefore an object of the present invention to provide an X-ray generator system with improved performance characteristics.

Another object of the present invention is the provision in an X-ray generator for obtaining a voltage output waveform having a short rise time and fall time and low ripple during steady-state conditions.

Yet another object of the present invention is the provision in a high-voltage transformer used in an X-ray generator system for having a low-leakage inductance, distributed capacitance, and skin effect.

Still another object of the present invention is the provision in an X-ray generator system for producing an improved output wave shape, while at the same time limiting the size of the transformer cooling tank.

Yet another object of the present invention is the provision for a high-voltage transformer whose performance characteristics are closely coupled with those of a pulse-width-modulated square-wave inverter in an X-ray generator system.

These objects and other features and advantages will become more readily apparent upon reference to the following description when taken in conjunction with the appended drawings.

Summary of the Invention

Briefly, in accordance with one aspect of the invention, a pulse-width-modulated inverter operates with a closely coupled high-voltage transformer and associated filter to provide a voltage output waveform with a very fast rise and decay time, a small ripple, and very good reproducibility with minimal distortion. The inverter provides a high-frequency variable voltage supply which is fed to the high-frequency, high-voltage step-up transformer having smaller core and coil dimensions than the conventional X-ray generator transformer, such that its performance characteristics are closely matched with those of the inverter. The smaller dimensions result in reduced leakage reactance and distributed capacitance in the transformer and, therefore, an improved output waveform of the system. An improved cooling system is provided to accommodate the higher heat losses which are generated by operating at higher frequencies and by the use of the smaller transformer.

By another aspect of the invention, the transformer coil is cooled with an evaporative cooling system with heat transfer characteristics that are vastly improved over the conventional mineral-oil method. The coolant used is liquid freon|13, which provides an enhanced cooling effect by the nature of its cycling between liquid and gaseous states. These enhanced heat-transfer characteristics allow the coil-winding wire to operate at much higher current and flux densities than those normally possible using conventional mineral-oil cooling.

In addition to the improved output waveform which results from the reduced leakage reactance and distributed capacitance, the transformer, itself, is substantially reduced in size and weight. For example, for the same output power the weight of the transformer can be reduced on the order of fifteen times.

In the drawings as hereinafter described, a preferred embodiment is depicted. However, various other modifications can be made thereto without departing from the true scope and spirit of the invention.

Brief Description of the Drawings

FIGURE 1 is a schematic illustration of the X-ray generator system in accordance with the preferred embodiment of the invention;

FIGURE 2 is a schematic illustration of the transformer portion thereof;

FIGURE 3 is a schematic illustration of the transformer and associated coolant tank in accordance with the preferred embodiment of the invention; and

FIGURES 4A and 4B are comparative illustrations of a prior art waveform and the improved output waveform from the present invention.

Description of the Preferred Embodiment

Referring now to FIGURE 1, there is shown schematically an X-ray generator system which receives three-phase ac. power from the main supply and delivers high-voltage, controlled d.c. power to an X-ray tube 11. The three-phase source is rectified by a bridge-connected, full-wave, silicon rectifier 12, and the output is filtered with a conventional capacitor-inductor filter 13. The filtered d.c. output is then fed into a pulse-width-modulated, transistor inverter 14 which converts it to a high frequency a.c. output. This inverter and its driving system is described in greater detail in copending U.S. Patent Applications Serial Nos. 564 538 and 564 612 filed concurrently herewith and incorporated herein by reference. Suffice it to say here, the output voltage of the inverter 14 is varied by adjusting the pulse width of each half cycle such that there is produced a high-frequency square-wave variable voltage output.

The output of the inverter 14 is applied to the primary winding of a high-voltage, high-frequency step-up transformer 16 which operates in conjunction with the inverter 14 at relatively high frequencies (i.e., in the range of 5-15 kHz) to produce a high voltage (i.e., up to 150 kV) a.c. output. The transformer 16 is uniquely constructed in such a manner as to exhibit desirable performance characteristics related to and closely coupled with the particular operating characteristics of the inverter 14. For example, in order to maintain a desired level of X-ray reproducibility, it is necessary that there be a minimal distortion of the square-wave output from the inverter. This is accomplished in the present invention by, inter alia, providing a high-voltage transformer 16 having a very low leakage reactance and low distributed capacitance. The close coupling is further accomplished by the use of an evaporative cooling process in obtaining improved performance characteristics from the transformer. These particular features of the transformer 16 will be more fully discussed hereinafter.

The output of the transformer 16 is applied to a high-voltage, full-wave silicon rectifier 17 whose d.c. output is then applied to a smoothing capacitor filter and voltage feedback network shown at 18. These components, and their interrelationship with the X-ray generating system is more fully discussed in the above-referenced copending patent applications.

Referring now to FIG. 2, the high-voltage transformer 16 is shown to include a magnetic core 21, a primary coil 22, and a secondary coil 23. In a preferred embodiment of the invention, the magnetic core 21 is composed of a nickel-iron alloy commonly known as Megaperm APL, having a Curie point of 310°C. When operating in accordance with the present invention, the flux density in the magnetic core 21 is in the range of .6 to 1.2 Tesla.

The primary coil 22 comprises a single winding as shown with its thickness or "build," as indicated by the dimension A, being minimized in order to minimize the leakage inductance of the transformer.

The secondary coil 23 is a multiple layered, pyramid-type winding to provide graded capacitance characteristics. To further minimize the leakage inductance, the secondary and primary are closely coupled with the distance therebetween, represented by "C," being minimized. The radius to the gap C is shown by the letter "P". The thickness B of the secondary winding is minimized, again, in order to minimize the leakage inductance, while the layered layer spacing, D, is maximized for the purpose of minimizing the distributive capacitance. The radius to the center of the secondary coil is shown by the letter "R".

In one embodiment of the invention, wherein the transformer 16 was constructed and operated with the above-described X-ray generator system, the characterizing features were as follows:

A - Thickness of primary winding: 4 mm.
B - Thickness of secondary winding: 30 mm.
C - Gap between primary and secondary: 6.8 mm.
D - Layer-to-layer spacing: 6.8 mm.
L - Length of secondary layer: 140-62 mm. pyramid
R - Radius of coil: 56 mm.

L - Lenght of secondary coil: 100 mm. mean; 140 mm. max., pyramid

N - Number of turns in the coil: PY 6-11 SY 2020 (2 coils per transformer

Area of magnet core: 33,600 mm.^{2}

Cross-sectional area of magnetic core: 1600 mm.^{2}

The above-described transformer is designed to operate in a frequency range of 5 to 15 kHz, with a flux density in the range of .6 to 1.2 Tesla, and a current density in the range of 4.65 to 20.4 amps/mm.^{2}.

When constructed as described above, and when operating with the inverter system and load characteristics discussed hereinabove, the transformer 16 exhibits a leakage reactance on the order of 2.5 percent when operating at 5 KHz. This is to be compared with the leakage inductance of 30-40 percent for a typical 12-pulse conventional transformer operating at 60 Hz. The distributed capacitance of the above-described transformer while operating under those conditions has been found to be 36 picofarads per coil.

As mentioned earlier an increase in operating frequency causes a concomitant increase in hysteresis losses in the core 21 to thereby cause the core temperature to rise significantly. There is shown in FIG. 3 an evaporative cooling system which accommodates these attendant temperature rises by way of a nucleate boiling process. The transformer 16 is mounted, by conventional means, in the lower portion of a tank 28. The tank 28 is partially filled with a coolant 29 having relatively high heat transfer characteristics and a relatively low boiling point. A preferred coolant liquid has been found to be a commercially available Freon 113 with a boiling point of 47^{o}C. at one atmosphere and a heat transfer ratio of .15 W/mm.^{2}. The air in the tank 28 is preferably evacuated to enhance the heat transfer characteristics; typically, it operates in the range of -1 atmosphere to +1 atmosphere, between cold and warm conditions, respectively.

As can be seen in FIG. 3, the liquid coolant 29 remains at all times at a level sufficiently high so as to entirely cover the transformer 16. As the transformer core 21 tends to rise in temperature, the heat transfers to the coolant 29. When the coolant 29 reaches its boiling point, it is vaporized and rises to the upper portion 29 of the tank 28. Here, it tends to cool and condense to fall back to the lower portion of the tank 28 for further cooling of the core 21. In this way, the evaporative cooling process is employed to cool the transformer core 21 in a much more efficient and effective manner than that of the conventional oil-filled transformer tank. These increased heat transfer characteristics accommodate the increased hysteresis losses that are characteristic of a transformer which has been reduced in size. The reduction in size, in turn, allows for the tailoring of the transformer architecture so as to reduce both the leakage reactance and the distributed capacitance which, in turn, allows for increased operating frequencies. The combination of these characteristics then allows for better waveform control in the output of the system.

Depending on the specific operating conditions and requirements of the system, it may be desirable to enhance the evaporative cooling process by way of additional cooling capabilities. One approach is to provide a plurality of hollow fins 31 at the upper end of portion 29 of the tank 28 with a fan 32 directed to blow air thereover so as to hasten the condensation process.

With the use of the nucleate boiling process described above, heat can be dissipated much more efficiently (up to 10 times the w/in^2) than with a conventional air radiation conduction process. The core can therefore be run at higher flux densities (i.e., 1.2 Tesla at 6 kHz versus 0.15 Tesla at 6 kHz) and frequencies than those recommended by the material manufacturer. This allows a reduction in the cross-sectional area and volume of the core to reduce the losses that would otherwise occur. Moreover, because of the higher frequency and flux densities in the core, the number of turns in the coil can be decreased to reduce the leakage reactance, distributed capacitance and resistance. Further, the increased cooling capabilities allow the coil to be operated at much higher current densities (i.e., 20 $A/mm.^2$ versus 2.6 $A/mm.^2$) which in turn allows a reduction in the wire diameters, coil length, and radial depth. With the benefit of these improved characteristics, a cumulative result is a reduction in the weight-to-power ratio of 30:1 for a 50 Hz core and coil assembly rated at 100 KW.

Referring now to FIG. 4A, there is shown an output waveform 32 which is representative of the output waveform from a conventional X-ray generator system. As will be seen, the rise time T_1 and decay time T_3 are relatively long when compared with the "useful time" or the time on "T ON". As a result, the useful time is short, as compared with the total elapsed time, thereby representing increase dosages during the rise and decay times.

More importantly, these relatively long rise and decay times tend to substantially reduce the capability of reproducing the same or similar outputs in successive exposures.

Also characteristic of the conventional output waveform is the fact that the steady state, or "useful time," portion has a relatively large ripple. Typically, a 12-pulse conventional transformer will produce an output having a ripple in the range of ten percent.

In contrast, the waveform output of the present invention is shown in FIG. 4B to have a relatively short rise times T1' and T3'. The time-on "T ON" period is substantially reduced from that of the conventional system, whereas the "useful time" is substantially equal thereto. In addition, the ripple during the useful time T_2 is substantially reduced from the ripple of the conventional system. Waveforms having a ripple on the order of 5 percent are consistently obtained with the present invention.

Because of the improved output waveform characteristics that can be obtained with the present transformer, the reproducibility thereof is substantially increased. In this regard, the present system has consistently performed with a coefficient of variation in the range of 0.01 to 0.03.

It will, of course, be understood that while the present invention has been described in terms of preferred and modified embodiments, it may well take on any number of forms while remaining within the scope and intent of the invention. Having thus described the invention, what is claimed is novel and desired to be secured by Letters Patent of the United States.

10374-15XZ-02523
GENERAL ELECTRIC COMPANY

CLAIMS

What is claimed is:

1. A cooling system for a high-voltage transformer for use in an X-ray generator system of the type having an inverter with a plurality of switching devices arranged in a full-bridge relationship to provide a high frequency a.c. output to the primary of the transformer comprising:

a tank capable of containing a liquid;

means for mounting the transformer in said tank;

a liquid coolant disposed in the lower portion of said tank in surrounding relationship with said transformer, said coolant having a heat-transfer ratio and a boiling point such that in normal operation of the transformer said coolant tends to vaporize within said tank; and

condensing means associated with the upper portion of said tank for condensing said coolant vapor and causing the resulting liquid to return to the lower portion of the tank.

2. A cooling system as set forth in Claim 1 wherein said liquid coolant comprises freon 113.

3. A cooling system as set forth in Claim 1 wherein said condensing means comprises a plurality of hollow fins extending from said tank and communicating with the upper portion of said tank so as to allow coolant vapor to enter said hollow fins.

4. A high-voltage transformer for use in an X-ray generator system of the type having an inverter with a plurality of switching devices arranged in full-bridge relationship for providing a high-voltage d.c. output to an X-ray tube, comprising:

an iron core for linking the flux in associated coils;

coil means comprising at least one primary and one secondary coil surrounding said core in flux-linking relationship, such that a current flow in said primary coil will cause a current flow in said secondary coil at a higher voltage, said coil means being so constructed as to exhibit a leakage inductance of less than 5 percent at normal operating conditions; and means for cooling said core to prevent its temperature from reaching its Curie point.

5. A high-voltage transformer as set forth in Claim 4 wherein said coil means comprises a coil with said primary and secondary coils being in concentric relationship.

6. A high-voltage transformer as set forth in Claim 4 wherein said coil means exhibits a distributed capacitance of less than 50 mF per coil.

7. A flux high-voltage transformer set forth in Claim 4 wherein said core is comprised of a nickel-iron alloy.

8. A high-voltage transformer set forth in Claim 7 wherein said core is adapted to operate at a flux density in the range of .6 to 1.2 Tesla.

9. A high-voltage transformer as set forth in Claim 4 wherein said cooling means includes: a liquid coolant surrounding said core and coil means, said liquid coolant having a relatively low boiling point and being capable of being vaporized by the heat from said core at temperatures below said Curie point; and means for condensing said vaporized coolant to its liquid form.

10. A high-voltage transformer as set forth in Claim 9 wherein said liquid coolant comprises freon 113.

11. An X-ray generator system comprising:

a d.c. source of relatively low voltage;

a square-wave inverter for receiving the output of said d.c. source and for providing a high-frequency output;

a high-frequency transformer for receiving the output of said inverter and for providing a high-voltage output, said transformer being capable of operating in the middle frequency ranges and being so constructed as to have a leakage inductance below 5 percent when operating at 5 KHz;

a rectifier for receiving said transformer output and providing a high-voltage d.c. output; and

a filter for smoothing the output from said rectifier for application to an X-ray tube.

12. An X-ray generator system as set forth in Claim 11 wherein said inverter is a pulse-width-modulated transistor inverter.

13. An X-ray generator system as set forth in Claim 11 wherein said high-frequency transformer is so constructed that in performance it operates with a distributed capacitance of less than 50 picofarads per coil.

14. An X-ray generation system as set forth in Claim 11 wherein said high-frequency transformer has primary and secondary coils arranged in concentric relationship.

15. An X-ray generation system as set forth in Claim 11 and including evaporative cooling means comprising:

a liquid coolant surrounding said high-frequency transformer and having a relatively low boiling point such that the transfer of heat from said high-frequency transformer causes said liquid coolant to boil off to form a vapor; and

means for condensing said vapor to a liquid form for return to the liquid coolant.

16. An X-ray generation system as set forth in Claim 15 wherein said liquid coolant comprises Freon-113.

0151729

1 / 2

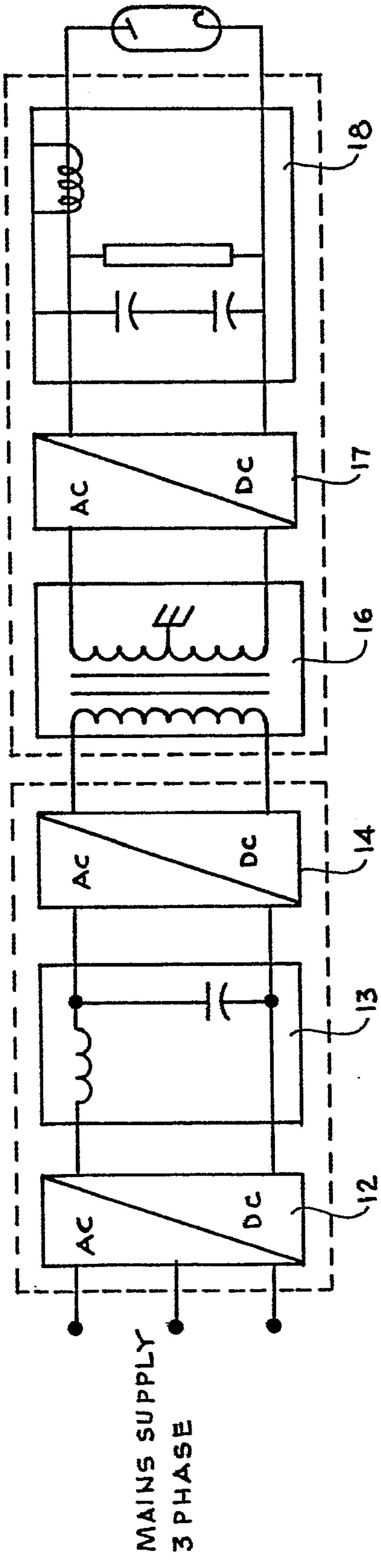

FIG. 1

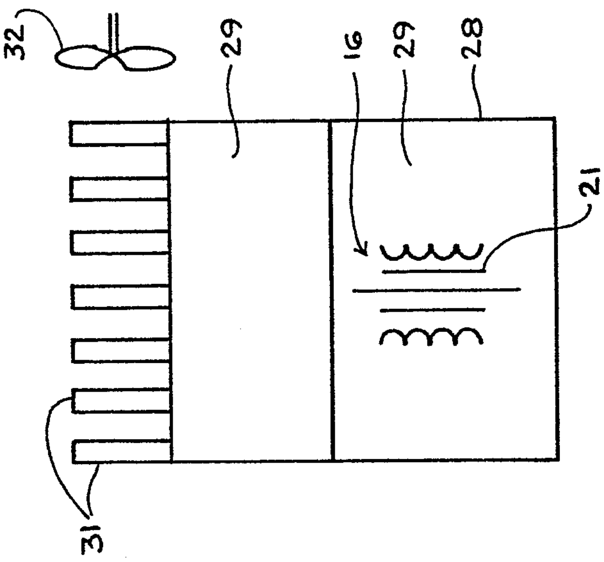

FIG. 3

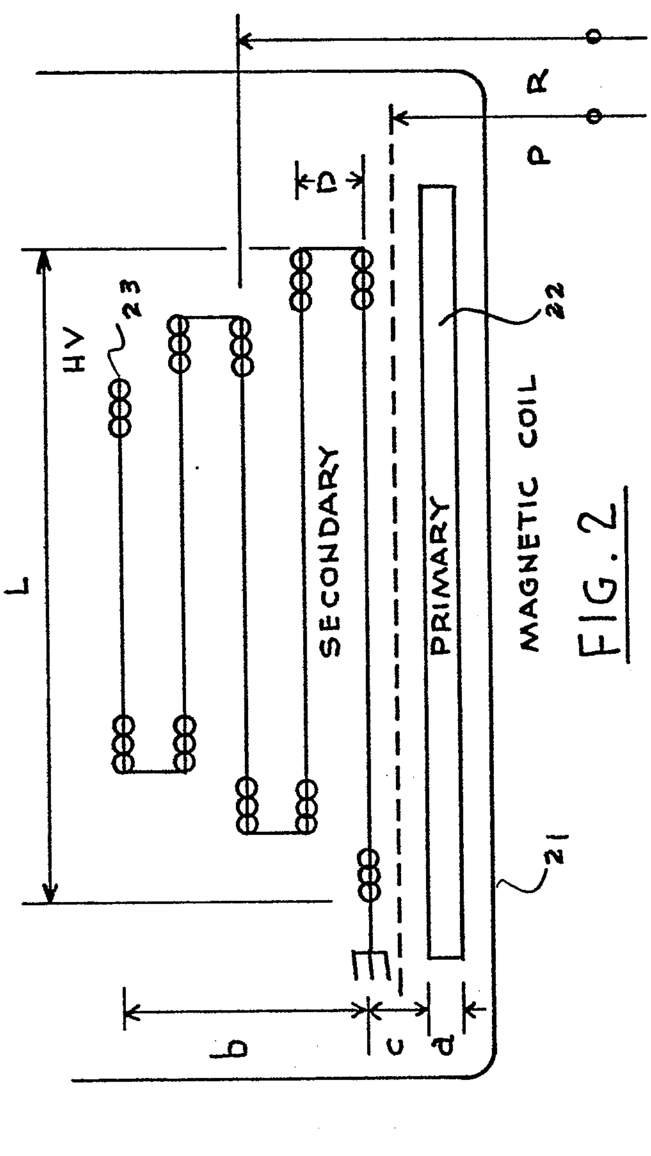

FIG. 2

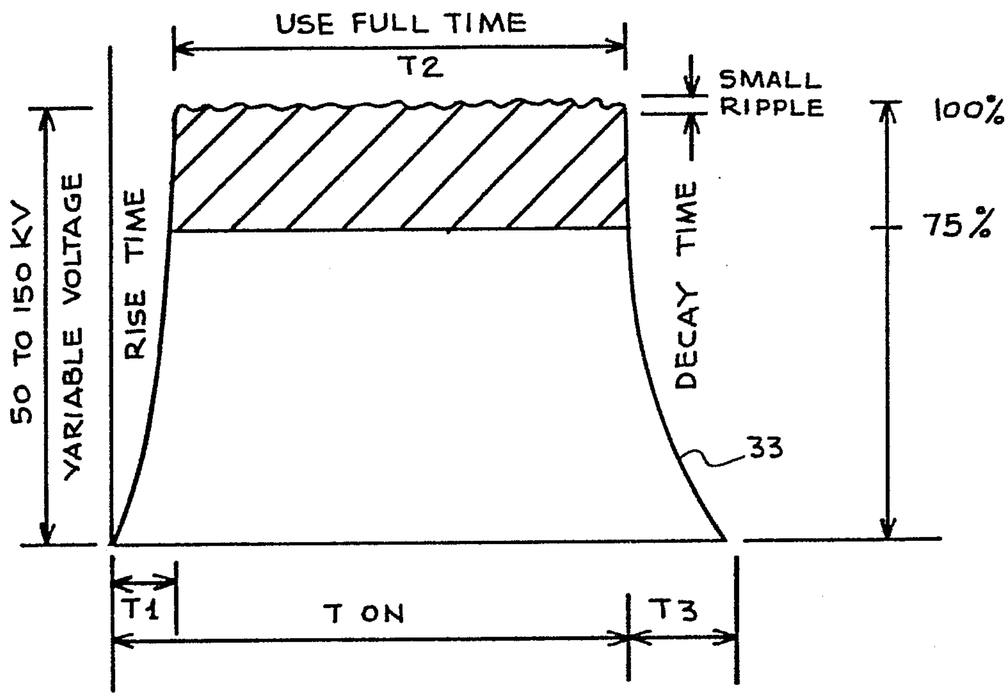
USE FULL TIME
T2
SMALL RIPPLE
100%
75%
50 TO 150 KV
VARIABLE VOLTAGE
RISE TIME
DECAY TIME
33
T1
T ON
T3

FIG 4B

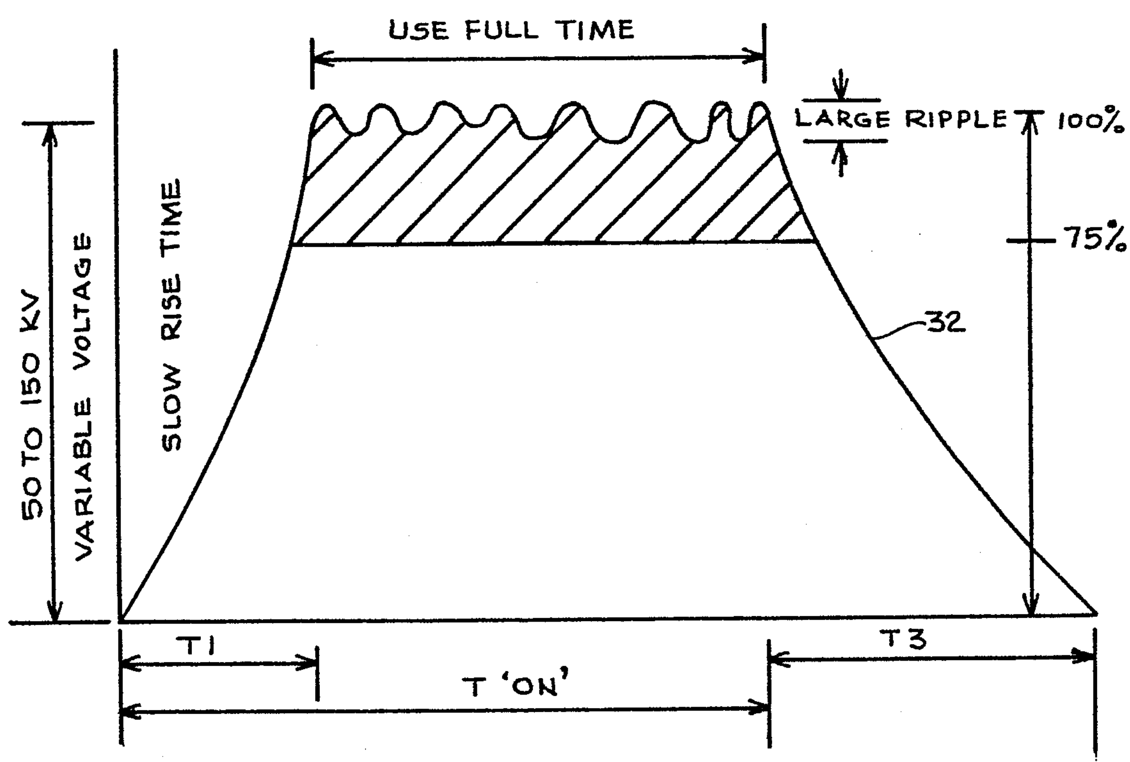
USE FULL TIME
LARGE RIPPLE
100%
75%
50 TO 150 KV
VARIABLE VOLTAGE
SLOW RISE TIME
32
T1
T 'ON'
T3

FIG. 4 A