Introduction:

A high voltage generator (HVG) in an X-ray system acts as the core power unit, converting low-voltage input (120-440VAC) into high-voltage electrical energy (typically 30 kV) to (150 kV) for medical, over (450 kV) for industrial) to accelerate electrons in the X-ray tube and produce X-ray photons. Modern units use high-frequency, constant-potential technology to minimize voltage ripple and ensure consistent, high-quality image production.

Transformers

➤ ***Autotransformer***

X – Ray operating consoles usually have adjustments labeled major KVp and minor KVp, and by selecting a combination of these controls the technologist can provide precisely the required KVp. The major KVp adjustment and the minor KVp adjustment represent two separate series of taps of ***the autotransformer*.** Selection of the appropriate taps can be made by an adjustment knob or by a push button. If the primary voltage to the autotransformer is 220 V, the output of the autotransformer can be controlled from about 100 to 400 V depending on the design of the autotransformer. This voltage becomes the input to the high-voltage step-up transformer in the high – voltage section that increases the voltage to provide the kilovoltage required.

The autotransformer is single winding around an iron core operates on self-induction principle, it designed to supply voltage of varying magnitude to the several different circuits of the x-ray machine, most prominently the filament circuit and the high-voltage circuit. The voltage supplied to the high-voltage transformer is controlled and variable. It is much safer and easier in terms of engineering to vary a low voltage and then increase it than to increase a low voltage to the kilovolt level and then vary its magnitude.

➤ ***High – voltage transformer:***

The high – voltage transformer is a step – up transformer, that is, the secondary (induced) voltage is greater than the primary (supply) voltage because the number of secondary windings is greater than the number of primary windings. The ratio of the number of secondary windings to the number of primary windings is called the turn's ratio.

The voltage increase is proportional to the turn's ratio, also the current is reduced proportionately. The turn's ratio of the high – voltage transformer is usually between 500 and 1000. Since transformers operate only on alternating current, the voltage waveform on both sides of a high – voltage transformer sinusoidal.

The only difference between the primary & secondary waveform is their amplitude. The primary voltage is measured in volt, and the secondary voltage is measured in kilovolts.

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad \textbf{(turn's ratio)}$$

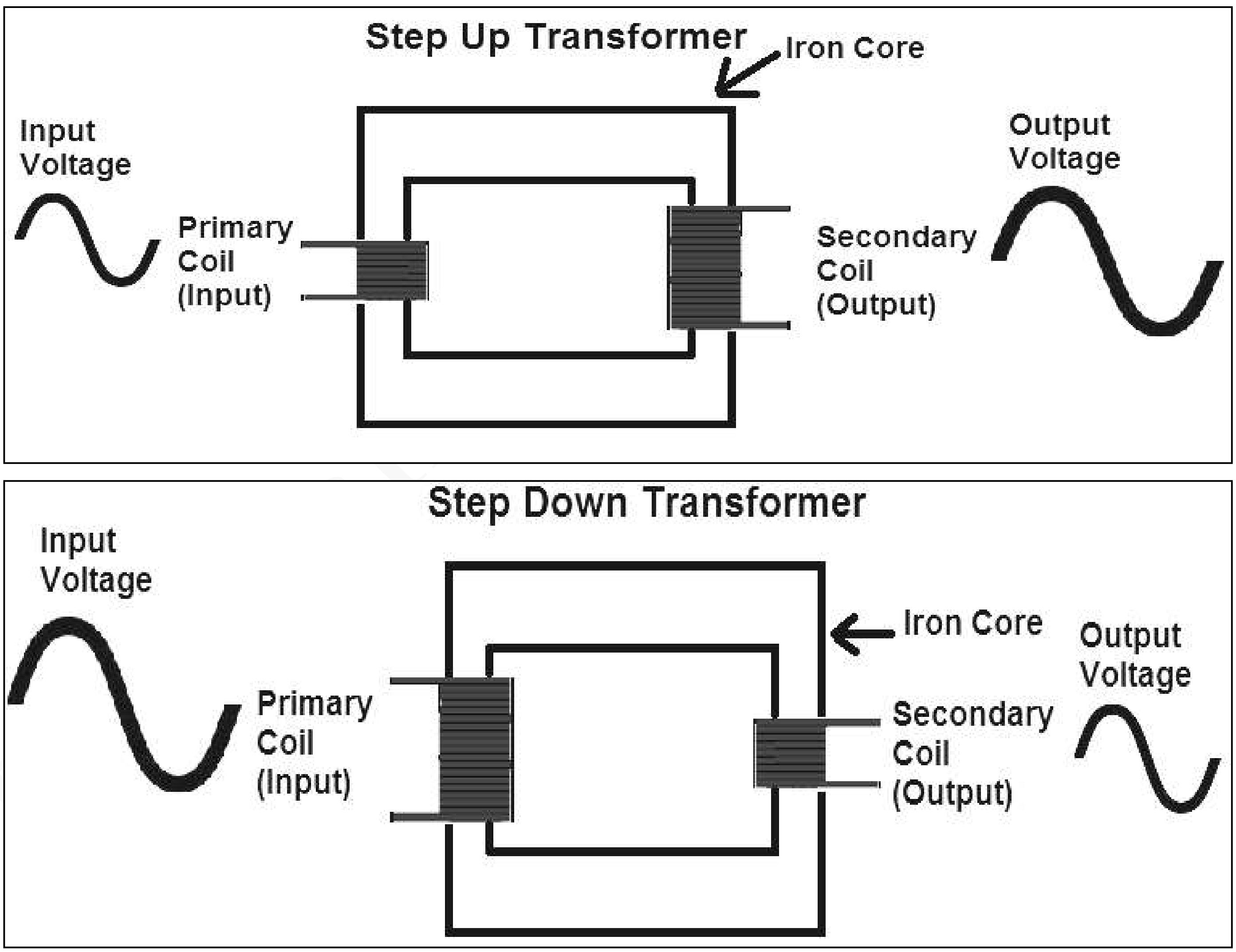


Fig. 1: Step-up transformer (top), step-down transformer (bottom).

Voltage rectification

Although transformers operate with alternating current, x – ray tubes must be provided with direct current. Rectification is the process of converting alternating voltage into direct voltage and therefore alternating current into direct current. Rectification is accomplished with device called diodes (two electrode).

➢ ***Types of voltage rectification:***

There are two types of voltage rectification:

⇘ ***Half – wave rectification:*** The inverse voltage is removed from the supply to the x – ray tube by rectification , this represents a condition in which the voltage is not allowed to swing negatively during the negative half of its cycle. Half – wave rectification is accomplished with two diodes placed in the high – voltage section.

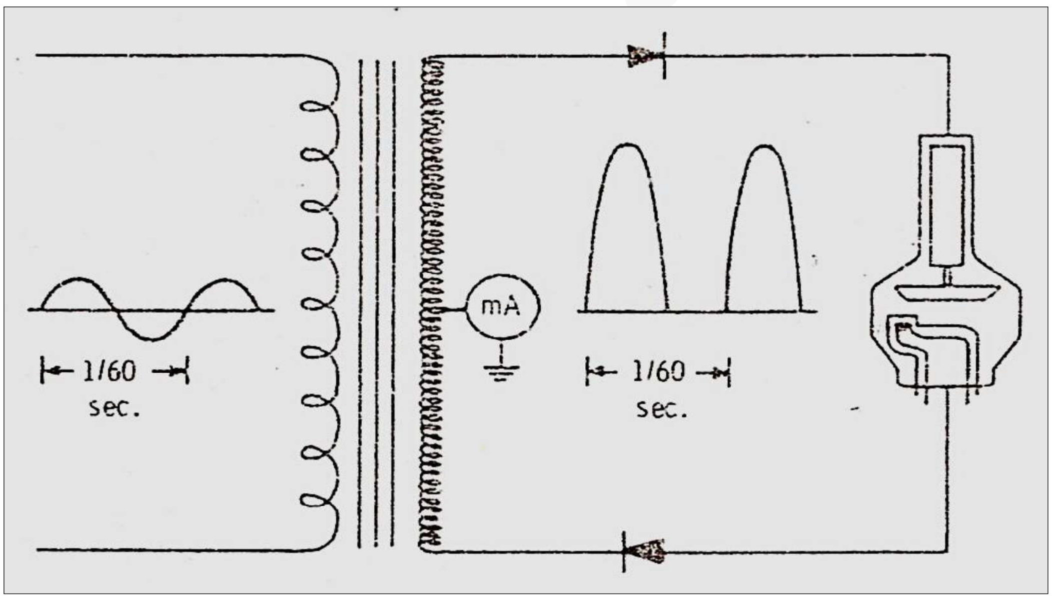


Fig 2: A half-wave - rectified circuit usually contains two diodes

⇘ ***Full – wave rectification:*** Full – wave rectified x- ray machine contain at least four diodes in the high voltage circuit . In Full – wave rectified circuit the negative half – cycle corresponding to the inverse voltage is reversed so that a positive voltage is always directed across the x – ray tube.

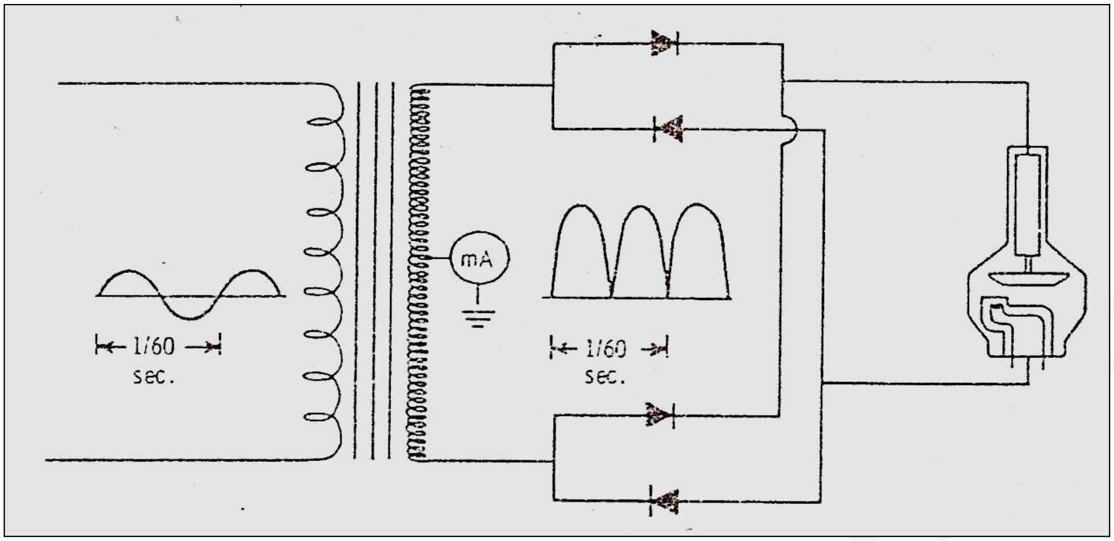


Fig 3: A full-wave—rectified circuit contains at least four diode

Phase power types

Generators

X-ray generator types include; single-phase, 3-phase, and high-frequency generators.

➤ **Single-Phase Generators**

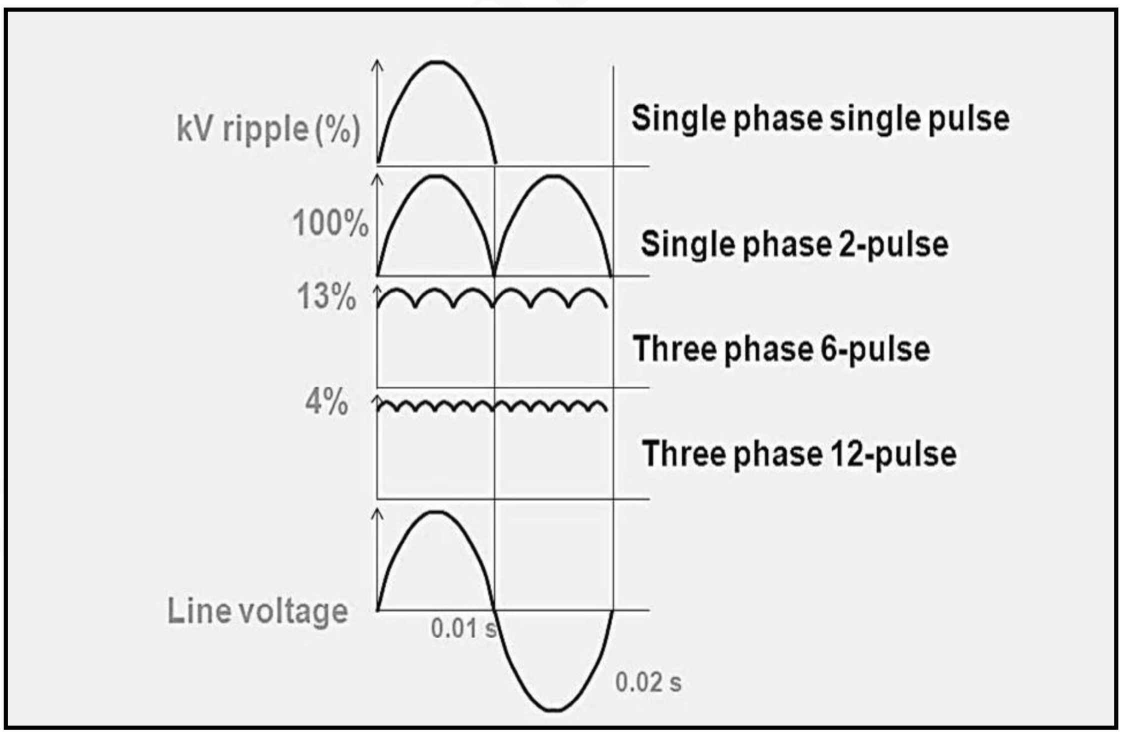
Single-phase, full-wave rectified generators produce two pulsations per cycle (120 pulsations per second) *with 100% voltage ripple*. With a constantly changing voltage potential, a spectrum of x-ray energies is produced with an average energy somewhere below peak kilovoltage. This pulsating beam results in a longer exposure time, and greater patient dose from lower energy soft x-rays. Single-phase generators are common for *dental radiography where teeth are relatively thin and longer exposure times are tolerable (no moving parts).*

➤ **Three-Phase Generators**

Voltage waveform has a value near zero The x –ray produced by the signal – phase,. This leads to a little diagnostic value because of their low energy and therefore low penetrability. One method of overcoming this deficiency is to employ the principle of generating three simultaneous voltage waveforms, such a manipulation result in a three – phase power. With three – phase power, multiple voltage waveforms are superimposed on one another, resulting in a waveform that maintains a nearly constant voltage, consequently, the voltage impressed across x – ray tube never dropping to zero during exposure.

A three-phase generator uses a three-phase AC line source for the purpose of creating more pulsations per unit time. This effectively reduces voltage ripple and increases the efficiency of x-ray production. A six-pulse generator delivers six pulsations per cycle, which reduces voltage ripple to 13% of kVp (see Fig. 4). Changing the wiring configuration produces 12 pulses per cycle (12-pulse generator), *reducing voltage ripple to 3%* of kVp. Using three-phase power results in greater photon output per unit of electrical input (mR/mAs) with higher average energy compared with single-phase units. Three-phase generators are expensive and rely on costly power line installations.

Fig: (4)



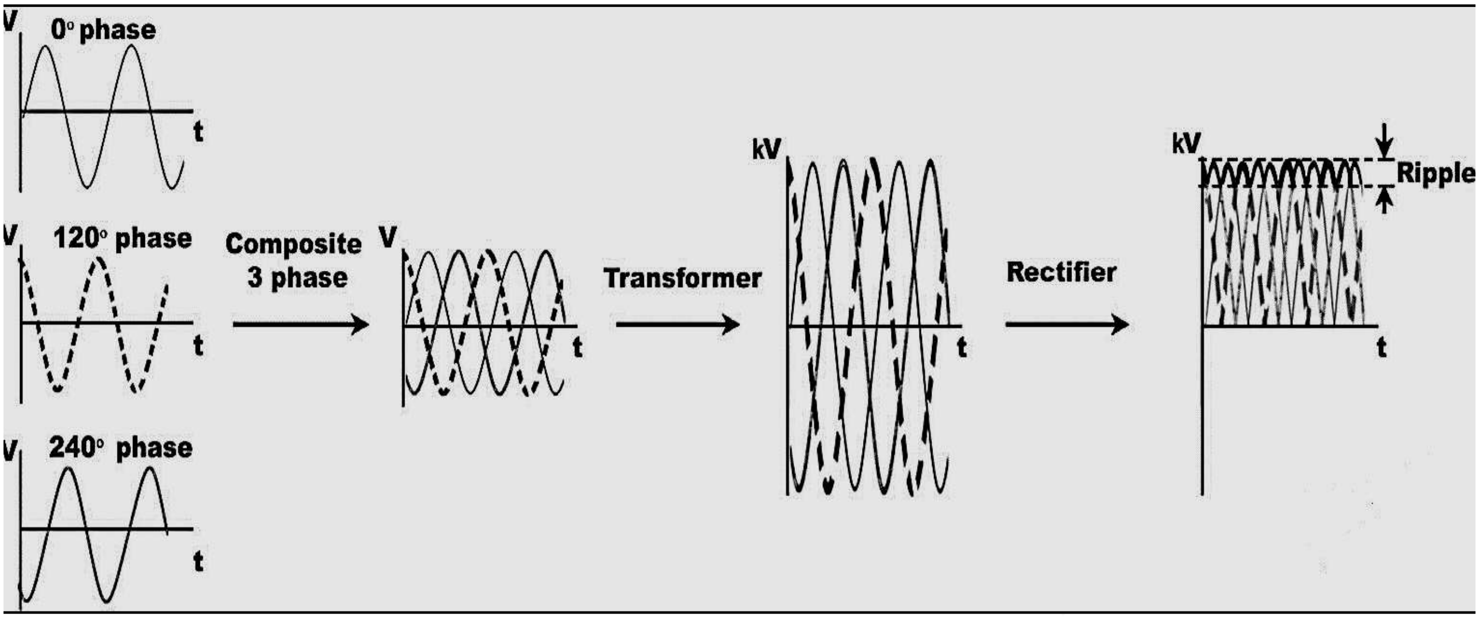
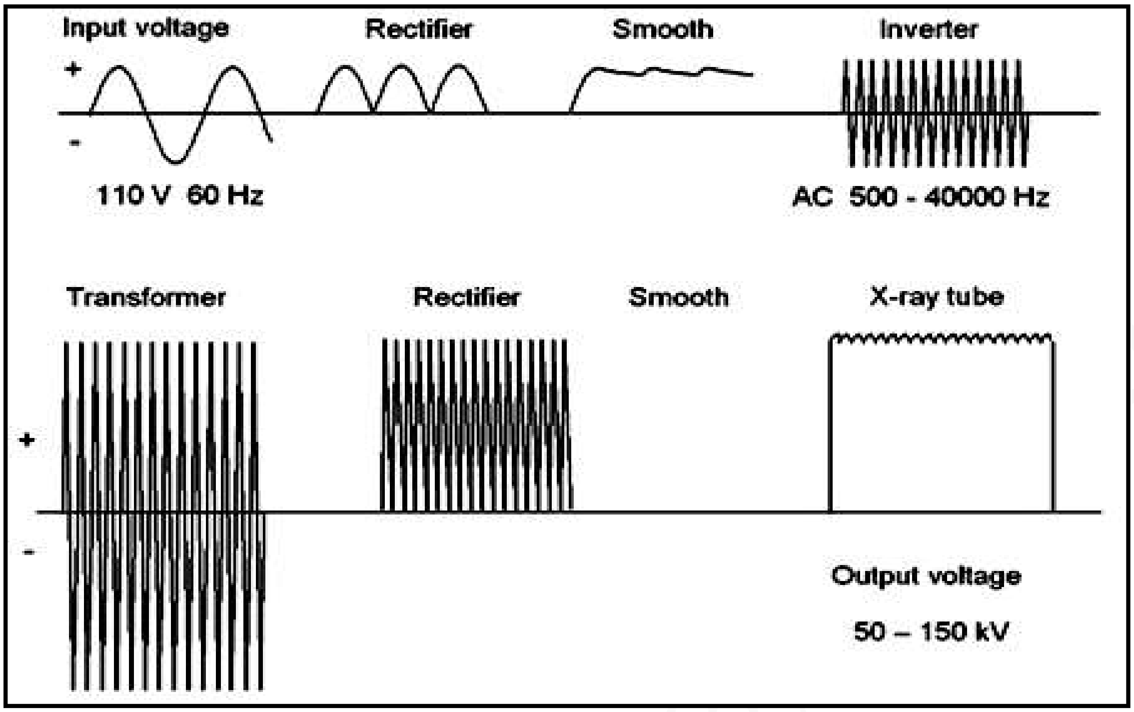


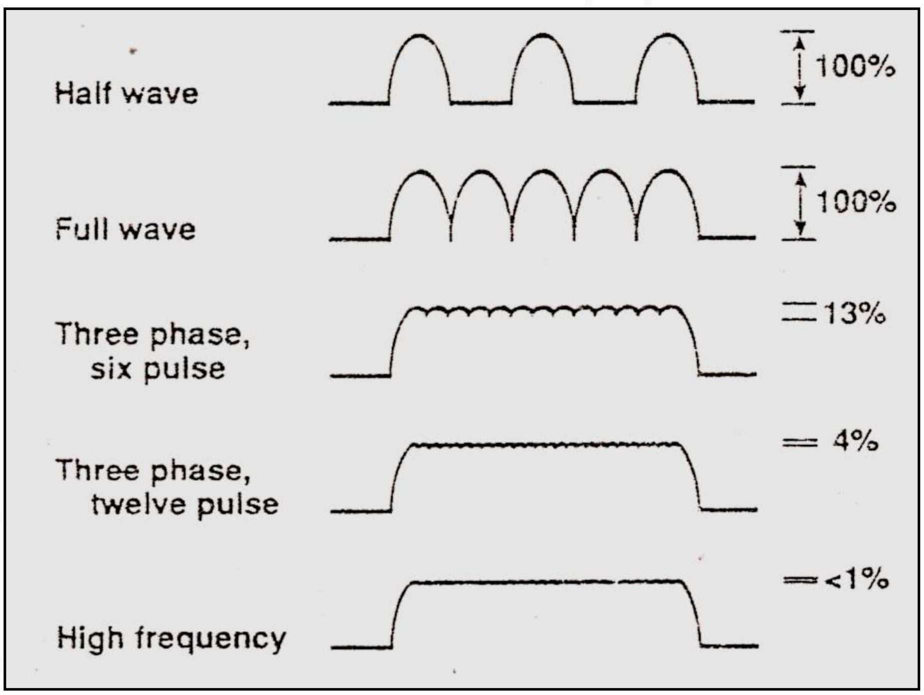
Fig 5: The voltage waveforms for single– phase, composed, amplified, and associated rectified.

The voltage drop from kVp is called *ripple* and represents the efficiency at which x-rays are produced. The greater the ripple, the less efficient the x-ray production. A kVp of zero accompanies 100% ripple. A voltage potential that drops below peak kilovoltage produces x-ray photons with a wide spectrum of energies.

➤ **High frequency generator:**

The development in high – voltage generator design was using a high – frequency electric circuit to the x – ray tube. Higher frequency would be obtained, consequently, when the voltage waveform are rectified and smoothed it has less than 1 % ripple, which is even better than three – phase power for x – ray production.





High-frequency generators are smaller and more efficient than three-phase generators. On the other hand, high-frequency generators have been the most widely used over the past decade for the following reasons:

– The standard frequency increase from 60 Hz to 500 KHz

– The highest average (effective) x-ray energy

– lower soft radiation dosage to patients

–Nearly constant potential waveform

– Smaller in design

– Increased radiation quality and quantity

– Shortest exposure time.

– Increase x-ray tube life.

X-ray circuits

X-ray circuits are designed to provide the necessary electrical power to an X-ray tube to generate, control, and accelerate electrons to produce X-ray radiation. The waveform of this power, which dictates how consistently high voltage is maintained, significantly impacts the efficiency of radiation output and the quality of the resulting image.

Components of X-ray Circuits

A complete X-ray machine circuit is divided into three main sections:

◣ **Primary Circuit:**

Main Switch/Fuses: Controls power input.

Line Voltage Compensator: Stabilizes incoming voltage to ensure consistent output.

Autotransformer: Adjusts the voltage to the step-up transformer, allowing the radiographer to set the desired kilovoltage (kVp).

Exposure Timer: Terminates the exposure after a precise, predetermined time, such as in Automatic Exposure Control (AEC) systems.

Filament Circuit:

Filament Step-down Transformer: Decreases input voltage (typically 120-220V) to low voltage (10-12V) and increases amperage (3-5A) to heat the cathode filament.

mA Selector: A rheostat that controls the temperature of the filament, which in turn determines the number of electrons released (tube current or mA).

◣ **Secondary Circuit:**

Step-up Transformer: Increases the voltage from the autotransformer to the kilovoltage required for X-ray production (40–150 kV).

Rectifier Unit: Solid-state diodes (rectifiers) convert alternating current (AC) from the transformer into direct current (DC), ensuring electrons flow only from the cathode to the anode.

<u>Effect of Waveform on Radiation Output</u>

The waveform, or the shape of the voltage signal applied to the X-ray tube, determines the efficiency of x-ray production.

Voltage Ripple: This is the variation in voltage between the peak (kVp) and minimum value. A lower ripple means more constant, higher-quality, and higher-quantity radiation.

Single-phase (100% Ripple): The voltage drops to zero 120 times per second, producing a large amount of low-energy ("soft") X-rays that are absorbed by the patient rather than contributing to the image.

Three-phase (13% - 4% Ripple): More efficient than single-phase, the voltage rarely drops to zero, resulting in a higher average voltage, increased beam intensity, and better penetration.

High-Frequency (Less than 3% Ripple): These generators produce nearly constant potential, which is the most efficient. They allow for shorter exposure times and higher average energies.

Effect of Waveform on Image Quality

The type of generator and its waveform directly influence image contrast and detail:

Improved Contrast and Penetration: Higher frequency and three-phase generators produce higher-energy beams (higher mean photon energy). This increases penetration power, which is ideal for dense body parts but may lower subject contrast in certain scenarios.

Reduced Patient Dose: Because higher-frequency generators produce fewer low-energy (soft) X-rays, they reduce the radiation dose delivered to the patient.

Higher Intensity/Quantity: For the same set technical factors (kVp, mA), high-frequency generators produce a higher quantity of photons (higher average mA) than lower-phase generators, enabling improved image quality and reducing the need for high mAs.