X-RAY MACHINE SYSTEM

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Radiology Equipment Technician I (X-Ray)

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Outline

X-RAY MACHINE SYSTEM:

Operating Console

- line compensation
- autotransformer
- kVp adjustment
- mA control
- exposure timer

*** High Voltage Generators:**

- transformers
- voltage rectification
- phase power types
- x-ray circuits

*** Effect of waveform on radiation output and image quality**

Objectives

The student should be able to do the followings;

- Mention three principal parts of an x- ray imaging system
- Differentiate between radiation quality and radiation quantity
- Mention the role operating console
- Explain the line compensation
- Analyze the role of each of the followings: autotransformer, kVp adjustment, ma control, Exposure timer, transformer, voltage rectification
- Draw the x-ray circuit
- Differentiate between phase power types
- Evaluate the effect of waveform on radiation output and image quality

X-ray Machine System

Three Principal Parts of an X- ray Imaging System
1. x-ray tube 2. operating console 3. high-voltage generator

OPERATING CONSOLE

The operating console allows the radiologic technologist to control the x-ray tube current and voltage so that the useful x-ray beam is of proper quantity and quality.

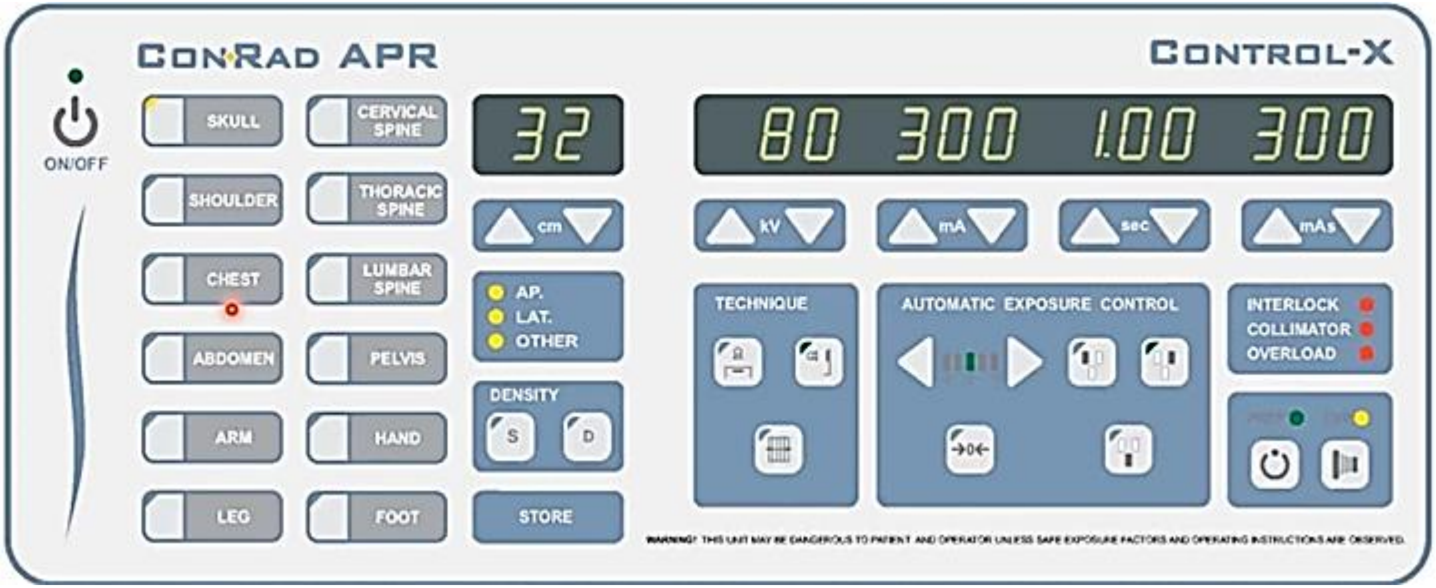
Radiation quantity refers to the number of x-rays or the intensity of the x-ray beam. Radiation quantity is usually expressed in milliroentgens (mR) or illiroentgens/milliampere-second (mR/mAs).

Radiation quality refers to the penetrability of the x-ray beam and is expressed in kilovolt peak (kVp) or, more precisely, half-value layer (HVL).

FIGURE 13-22 Anatomically programmed radiography operating console. Technique exposure control for patient size, body part, and position is automatically selected. (Courtesy Holly Evans-McDaniel, Shimadzu Medical Systems.)

operating console

- Operating console allows radiologists to control x-ray tube current and voltage to control the beam quality and quantity
- Radiation quantity refers to number of x-rays (intensity)
- Radiation quality refers to penetrability of x-ray beam and it expressed in kVp



operating console

The operating console usually provides for control of **line compensation**, kVp, mA, and exposure time. Meters are provided for monitoring kVp, mA, and exposure time. Some consoles also provide a meter for mAs. Imaging systems that incorporate automatic exposure control (AEC) may have separate controls for mAs. Most operating consoles are based on computer technology. Controls and meters are digital, and techniques are selected with a touch screen. Numeric technique selection is sometimes replaced by icons indicating body part, size, and shape. Many of the features are automatic, but the radiologic technologist must know their purpose and proper use. Most x-ray imaging systems are designed to operate on 220 V power, although some can operate on 110 V or 440 V. Unfortunately, electric power companies are not capable of providing 220 V accurately and continuously. Because of variations in power distribution to the hospital and in power consumption by various sections of the hospital, the voltage provided to an x-ray unit easily may vary by as much as 5%. Such variation in supply voltage results in a large variation in the x-ray beam, which is inconsistent with production of highquality images.

operating console

All of the electric circuits that connect the meters and controls on the operating console are at low voltage to minimize the possibility of hazardous shock. Figure 5-6 is a simplified schematic diagram for a typical operating console. A look inside an operating console will indicate how simplified this schematic drawing is! Operating consoles are based on computer technology. Controls and meters are digital, and techniques are selected with a touch screen. Numeric technique selection is often replaced by icons indicating the body part, size, and shape. Many of the features are automatic, but the radiologic technologist must know their purpose and proper use.

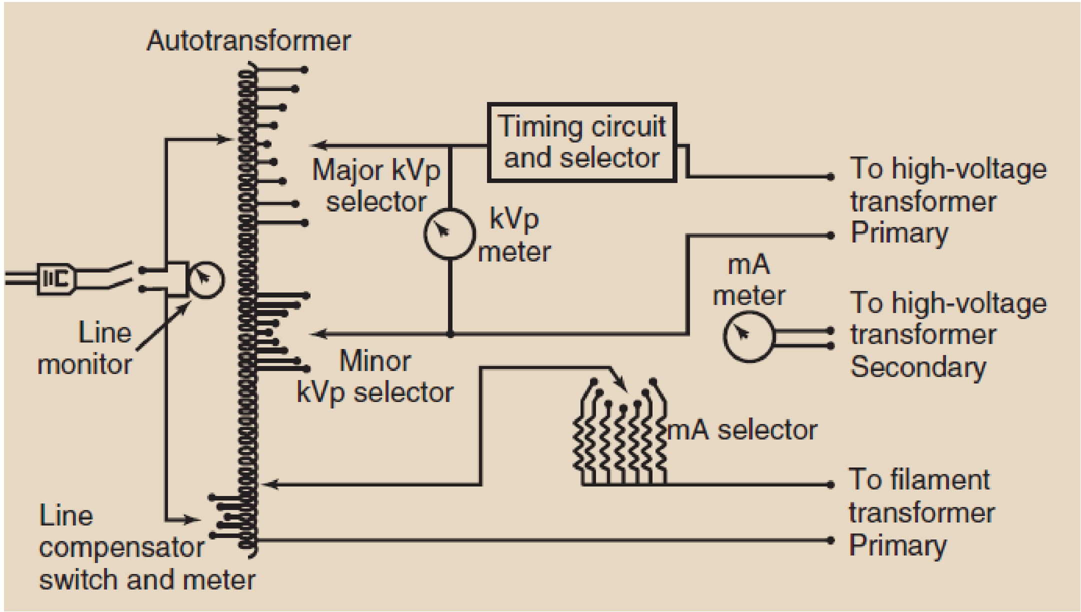


FIGURE 5-6 Circuit diagram of the operating console, with controls and meters identified.

AUTOTRANSFORMER

The power supplied to the x-ray imaging system is delivered first to the autotransformer. The voltage supplied from the autotransformer to the high-voltage transformer is variable but controlled. It is much safer and easier to control a low voltage and then increase it than to increase a low voltage to the kilovolt level and then control its magnitude.

The autotransformer has a single winding and is designed to supply a precise voltage to the filament circuit and to the high-voltage circuit of the x-ray imaging system. The autotransformer works on the principle of electromagnetic induction but is very different from the conventional transformer. It has only one winding and one core. This single winding has a number of connections along its length (Figure 5-7).

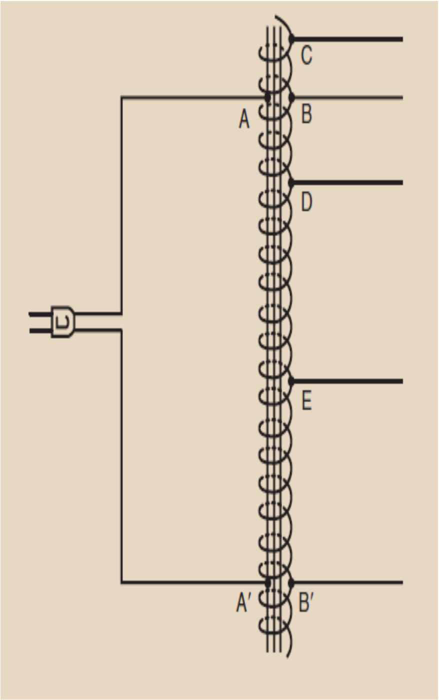


FIGURE 5-7 Simplified diagram of an autotransformer.

AUTOTRANSFORMER

Two of the connections, *A* and *A′* as shown in the figure, conduct the input power to the autotransformer and are called *primary connections.* Some of the secondary connections, such as *C* in the figure, are located closer to one end of the winding than are the primary connections. This allows the autotransformer to increase voltage. Other connections, such as *D* and *E* in the figure, allow a decrease in voltage. The autotransformer can be designed to step up voltage to approximately twice the input voltage value. Because the autotransformer operates as an induction device, the voltage it receives (the primary voltage) and the voltage it provides (the secondary voltage) are related directly to the number of turns of the transformer enclosed by the respective connections. The autotransformer law is the same as the transformer law.

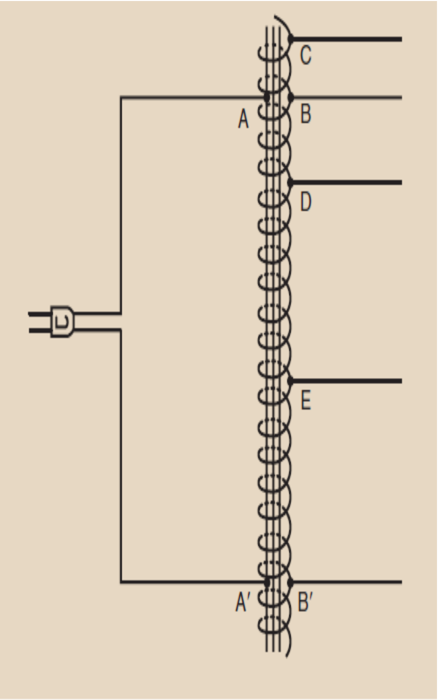


FIGURE 5-7 Simplified diagram of an autotransformer.

AUTOTRANSFORMER

AUTOTRANSFORMER LAW

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

where

V_p = the primary voltage

V_S = the secondary voltage

N_P = the number of windings enclosed by primary connections

N_S = the number of windings enclosed by secondary connections

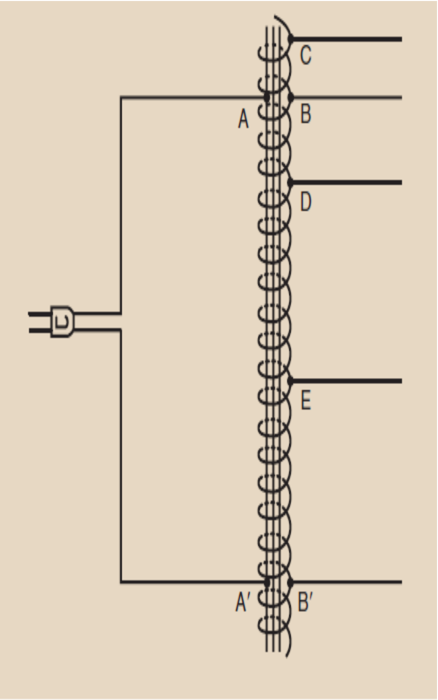


FIGURE 5-7 Simplified diagram of an autotransformer.

Adjustment of Kilovolt Peak (kVp)

Some older x-ray operating consoles have adjustment controls labeled **major kVp** and **minor kVp**; by selecting a combination of these controls, radiologic technologists can provide precisely the required kilovolt peak. The minor kilovolt peak adjustment “fine tunes” the selected technique. The major kilovolt peak adjustment and the minor kilovolt peak adjustment represent two separate series of connections on the autotransformer.

kVp determines the quality of the x-ray beam.

Control of Milliamperage (mA)

The x-ray tube current, crossing from cathode to anode, is measured in milliamperes (mA). The number of electrons emitted by the filament is determined by the temperature of the filament. The filament temperature is in turn controlled by the filament current, which is measured in amperes (A). As filament current increases, the filament becomes hotter, and more electrons are released by thermionic emission. Filaments normally operate at currents of 3 to 6 A. A correction circuit has to be incorporated to counteract the *space charge effect.* As the kVp is raised, the anode becomes more attractive to the electrons that would not have enough energy to leave the filament area. These electrons also join the electron stream, which effectively increases the mA with kVp.

- Thermionic emission is the release of electrons from a heated filament.

Control of Milliamperage (mA)

X-ray tube current is controlled through a separate circuit called the *filament circuit* (Figure 5-8). Connections on the autotransformer provide voltage for the filament circuit. Precision resistors are used to reduce this voltage to a value that corresponds to the selected milliamperage. X-ray tube current normally is not continuously variable.

Precision resistors result in fixed stations that provide x-ray tube currents of 100, 200, or 300 mA, and higher. The **falling load generator** constitutes an exception.

In a falling load generator the exposure begins at maximum mA, and the mA drops as the anode heats. The result is minimum exposure time.

The product of x-ray tube current (mA) and exposure time(s) is mAs, which is also electrostatic charge (C).

Control of Milliamperage (mA)

Question: An autotransformer connected to a 440-V supply contains 4000 turns, all of which are enclosed by the primary connections. If 2300 turns are enclosed by secondary connections, what voltage is supplied to the high-voltage generator?

Answer:

$$V_S = V_P\left(\frac{N_S}{N_P}\right)$$
$$= (440\ V)\left(\frac{2300}{4000}\right)$$
$$= (440\ V)(0.575)$$
$$= 253\ V$$

Question: If the autotransformer in Figure 5-7 is supplied with 220 V to the primary connections AA′, which enclose 500 windings, what is the secondary voltage across BB′ (500 windings), CB′ (700 windings), and DE (200 windings)?

Answer:

$$BB:\ V_S = V_P\left(\frac{N_S}{N_P}\right)$$
$$= (220\ V)\left(\frac{500}{500}\right) = 220\ V$$
$$CB:\ V_S = (220\ V)\left(\frac{700}{500}\right)$$
$$= (220\ V)\ (1.4) = 308\ V$$
$$DE:\ V_S = (220\ V)\left(\frac{200}{500}\right)$$
$$= (220\ V)\ (0.4) = 88\ V$$

Question: An image is made at 400 mA and an exposure time of 100 ms. Express this in mAs and as the total number of electrons.

Answer:

$$100\ ms = 0.1\ s$$
$$(400\ mA)\ (0.1\ s) = 40\ mAs$$
$$40\ mAs = (40\ mC/s)\ (s)$$
[remember, 1 A = 1 C/s]
$$= 40\ mC$$
$$= (40 \times 10^{-3}\ C)\ (6.3 \times 10^{18}\ e^-/C)$$
$$= 2.52 \times 10^{15}\ \mathbf{e^-}$$
$$= 2.52 \times 10^{17}\ \text{electrons}$$

Question: A filament transformer with a turns ratio of $\frac{1}{10}$ provides 6.2 A to the filament. What is the current through the primary coil of the filament transformer?

Answer: $\frac{I_P}{I_S} = \frac{N_S}{N_P}$ where I_P = primary current,

I_S = secondary current and $\frac{N_S}{N_P}$ = turns ratio

$$I_P = I_S\left(\frac{N_S}{N_P}\right)$$
$$= (6.2)\left(\frac{1}{10}\right)$$
$$= 0.62\ A$$

Control of Milliamperage (mA)

X-ray tube current is monitored with an mA meter that is placed in the tube circuit. The mA meter is connected at the center of the secondary winding of the high-voltage step-up transformer. The secondary voltage is alternating at 60 Hz such that the center of this winding is always at zero volts (Figure 5-9). In this way, no part of the meter is in contact with the high voltage, and the meter may be safely put on the operating console. Sometimes this meter allows that mAs can be monitored in addition to mA.

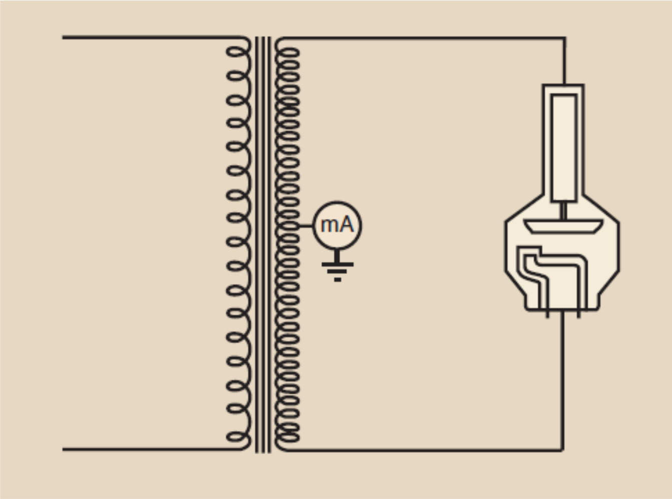


FIGURE 5-9 The mA meter is in the x-ray tube circuit at a center tap on the output of the high-voltage step-up transformer. This ensures electrical safety.

Filament Transformer

The full title for this transformer is the filament heating isolation step-down transformer. It steps down the voltage to approximately 12 V and provides the current to heat the filament. Because the secondary windings are connected to the high-voltage supply for the x-ray tube, the secondary windings are heavily insulated from the primary.
In the filament transformer the primary windings are of thin copper and carry a current of 0.5 to 1 A and approximately 150 V. The secondary windings are thick and at approximately 12 V electric potential, and carry a current of 5 to 8 A (not mA!).

EXPOSURE TIMERS

For any given radiographic examination, the number of x-rays that reach the image receptor is directly related to both the x-ray tube current and the time that the x-ray tube is energized. X-ray operating consoles provide a wide selection of x-ray beam-on times and, when used in conjunction with the appropriate mA station, provide an even wider selection of values for mAs. Paramount in the design of all timing circuits is that the radiographer starts the exposure and the timer stops it. During fluoroscopy, if the radiographer releases the exposure switch or the fluoroscopic foot switch, the exposure is terminated immediately. As an additional safety feature, another timing circuit is activated on every radiographic exposure. This timer, called a *guard timer*, will terminate an exposure after a prescribed time, usually approximately 6 s. Thus it is not possible for any timing circuit to continuously irradiate a patient for an extensive period. The timer circuit is separate from the other main circuits of the x-ray imaging system. It consists of an electronic device whose action is to "make" and "break" the high voltage across the x-ray tube. This is nearly always done on the **primary side** of the high-voltage transformer, where the voltage is lower. There are four types of timing circuits. Three are controlled by the radiologic technologist, and one is automatic. After studying this section, try to identify the types of timers on the imaging systems you use.

EXPOSURE TIMERS

Question: A KUB examination (radiography of the kidneys, ureters, and bladder) calls for 70 kVp, 40 mAs. If the radiologic technologist selects the 200 mA station, what exposure time should be used?

Answer: $$\frac{40\ \text{mAs}}{200\ \text{mAs}} = 0.20\ \text{s} = 200\ \text{ms}$$

Question: A lateral cerebral angiogram calls for 74 kVp, 20 mAs. If the generator has a 1000-mA capacity, what is the shortest exposure time possible?

Answer: $$\frac{20\ \text{mAs}}{1000\ \text{mA}} = 0.02\ \text{s} = 20\ \text{ms}$$

HIGH-VOLTAGE GENERATOR

The high-voltage generator of an x-ray imaging system is responsible for increasing the output voltage from the autotransformer to the kVp necessary for x-ray production.

A cutaway view of a typical high-voltage generator is shown in Figure 5-12.

Although some heat is generated in the high-voltage section and is conducted to oil, the oil is used primarily for electrical insulation.

The high-voltage generator contains three primary parts: the *high-voltage transformer*, the *filament transformer*, and *rectifiers*.

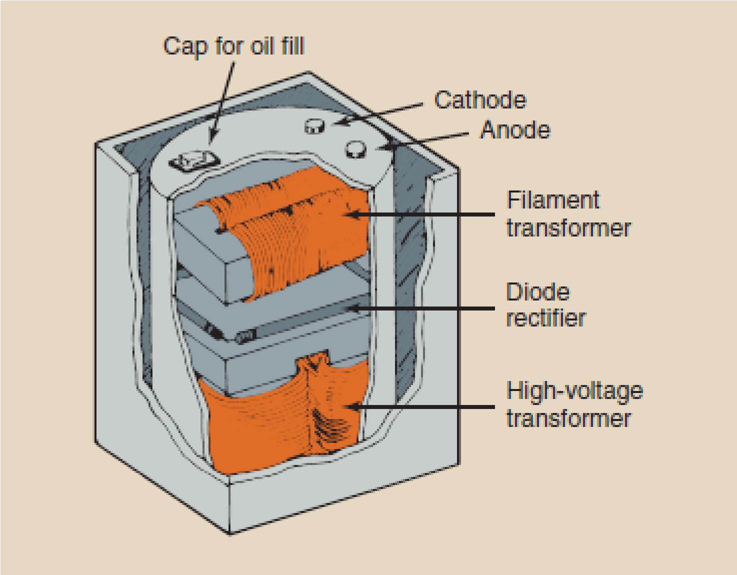


FIGURE 5-12 Cutaway view of a typical high-voltage generator showing oil-immersed diodes and transformers.

High-Voltage Transformer

The high voltage transformer is a step-up transformer, that is, the secondary voltage is higher than the primary 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 **turns ratio.**

The voltage increase is proportional to the turns ratio, according to the transformer law. Also, the current is reduced proportionately. The turns ratio of a high-voltage transformer is usually between 500 : 1 and 1000 : 1. Because *transformers operate only on alternating current*, the voltage waveform on both sides of a high-voltage transformer is sinusoidal (Figure 5-13).

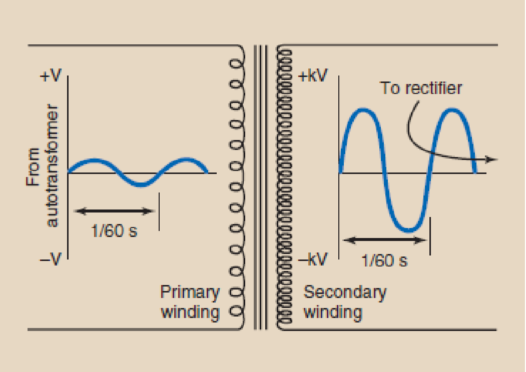


FIGURE 5-13 Voltage induced in the secondary winding of a high-voltage step-up transformer is alternating like the primary voltage but has a higher value.

High-Voltage Transformer

The only difference between the primary and secondary waveforms is their **amplitude**. The primary voltage is measured in volts (V), and the secondary voltage is measured in kilovolts (kV). The primary current is measured in amperes (A), and the secondary current is measured in milliamperes (mA).

EXAMPLE

Q: The turns ratio of a high-voltage transformer is 700 : 1, and the supply voltage is peaked at 120 V. What is the secondary voltage supplied to the x-ray tube?

Answer: (120 Vp) (700 : 1) = 84,000 Vp = 84 kVp

Voltage Rectification

The current from a common wall plug is 60 Hz alternating current (AC). The current changes direction 120 times each second. However, an x-ray tube requires a direct current (DC), that is, electron flow in only one direction. Therefore, some means must be provided for converting AC to DC.

The electronic device that allows current flow in only one direction is a **rectifier.** Although transformers operate with alternating current, x-ray tubes must be provided with direct current. X-rays are produced by the acceleration of electrons from the cathode to the anode and cannot be produced by electrons flowing in the reverse direction, from anode to cathode. Voltage rectification is required to ensure that electrons flow from x-ray tube cathode to anode only.

Voltage Rectification

The inverse voltage is removed from the supply to the x-ray tube by rectification. **Half-wave rectification** (Figure 5-18) is a condition in which the voltage is not allowed to swing negatively during the negative half of its cycle. Rectifiers are assembled into electronic circuits to convert alternating current into the direct current necessary for the operation of an x-ray tube (Figure 5-19). During the positive portion of the AC waveform, the rectifier allows electric current to pass through the x-ray tube. During the negative portion of the AC waveform, however, the rectifier does not conduct, and thus no electric current is allowed. The resultant electric current is a series of positive pulses separated by gaps when the negative current is not conducted. This resultant electric current is a rectified current because electrons flow in only one direction. This form of rectification is called *half-wave rectification* because only one half of the AC waveform appears in the output.

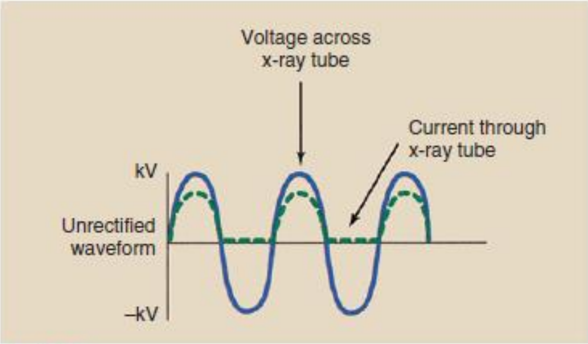


FIGURE 5-17 Unrectified voltage and current waveforms on the secondary side.

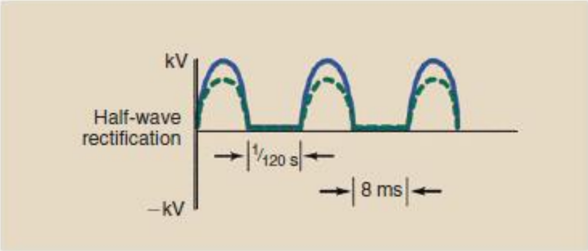


FIGURE 5-18 Half-wave rectification.

Single-Phase Power

All of the voltage waveforms discussed so far are produced by single-phase electric power. Single-phase power results in a pulsating x-ray beam. This is caused by the alternate swing in voltage from zero to maximum potential 120 times each second under full-wave rectification. The x-rays produced when the single-phase voltage waveform has a value near zero are of little diagnostic value because of their low energy; such x-rays have low penetrability. One method of overcoming this deficiency is to use some sophisticated electrical engineering principles to generate three simultaneous voltage waveforms that are out of step with one another. Such a manipulation results in three-phase electric power.

Three-Phase Power

The engineering required to produce three-phase power involves the manner in which the high-voltage step-up transformer is wired into the circuit, the details of which are beyond the scope of this discussion. Figure 5-23 shows the voltage waveforms for single-phase power, three-phase power, and full-wave–rectified three-phase power.

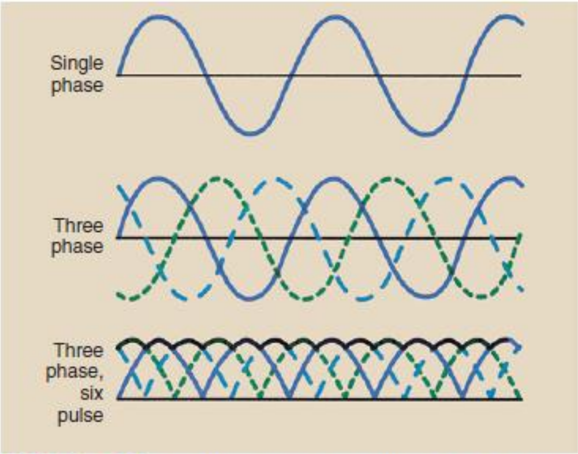


FIGURE 5-23 Three-phase power is a more efficient way to produce x-rays than is single-phase power. Shown are the voltage waveforms for unrectified single-phase power, unrectified three-phase power, and rectified three-phase power.

Voltage Ripple

Another way to characterize these voltage waveforms is by **voltage ripple.** Single-phase power has *100% voltage ripple*: The voltage varies from zero to its maximum value. Three-phase, six-pulse power produces voltage with only approximately *14% ripple*; consequently, the voltage supplied to the x-ray tube never falls to below 86% of the maximum value. A further improvement in three-phase power results in 12 pulses per cycle rather than 6. Three-phase, 12-pulse power results in only *4% ripple*; therefore, the voltage supplied to the x-ray tube does not fall to below 96% of the maximum value.

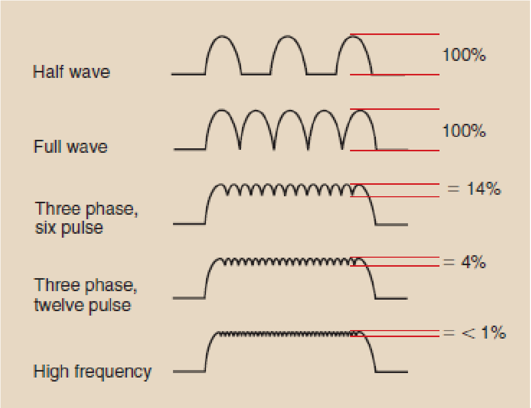


FIGURE 5-29 Voltage waveforms resulting from various power supplies. The ripple of the kilovoltage is indicated as a percentage for each waveform.

High-frequency generators have approximately *1% ripple* and therefore even greater x-ray quantity and quality. Figure 5-29 shows these various power sources and the resultant voltage waveforms they provide to the x-ray tube, as well as the approximate voltage ripple. The most efficient method of x-ray production also involves the waveform with the lowest voltage ripple.

X-RAY CIRCUIT

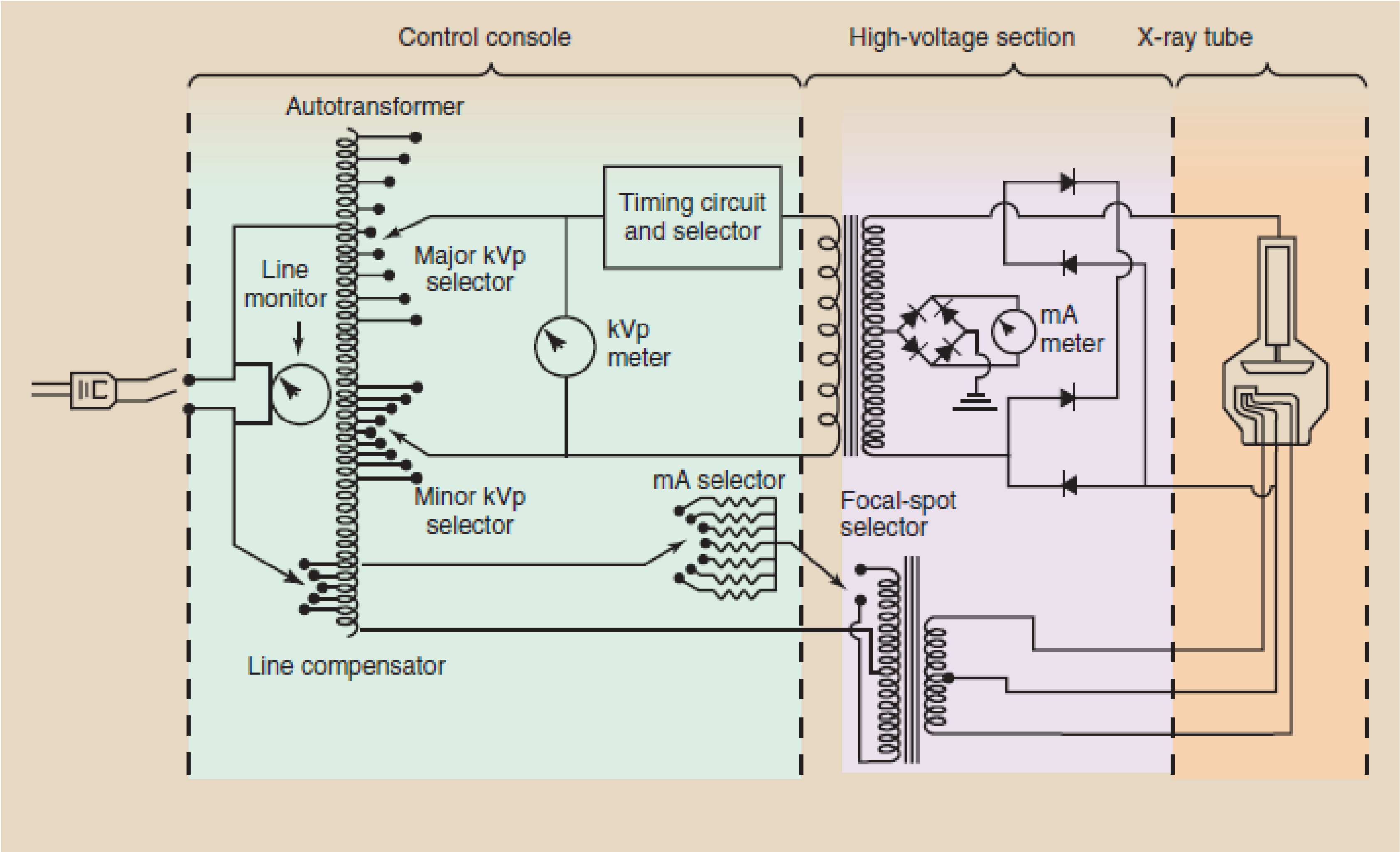


FIGURE 5-32 The schematic circuit of an x-ray imaging system.

Effect of Voltage Waveform

There are five voltage waveforms: half-wave–rectified, full-wave–rectified, three-phase/six-pulse, three-phase/12-pulse, and high-frequency waveforms.Half-wave–rectified and full-wave–rectified voltage waveforms are the same except for the frequency of x-ray pulse repetition. There are twice as many x-ray pulses per cycle with full-wave rectification as with halfwave rectification.

The difference between three-phase/six-pulse and three-phase/12-pulse power is simply the reduced ripple obtained with 12-pulse generation compared with sixpulse generation. High-frequency generators are based on fundamentally different electrical engineering principles. They produce the lowest voltage ripple of all high-voltage generators.

Effect of Voltage Waveform

Figure 7-15 shows an exploded view of a full-wave– rectified voltage waveform for an x-ray imaging system operated at 100 kVp. Recall that the amplitude of the waveform corresponds to the applied voltage and that the horizontal axis represents time.

At t = 0, the voltage across the x-ray tube is zero, indicating that at this instant, no electrons are flowing and no x-rays are being produced.

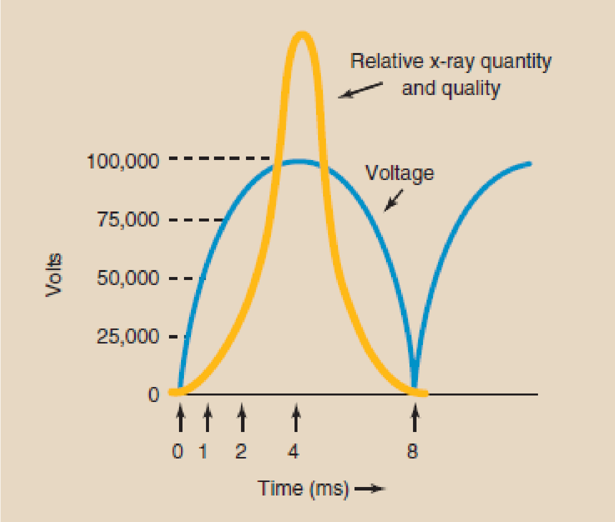


FIGURE 7-15 As the voltage across the x-ray tube increases from zero to its peak value, x-ray intensity and energy increase slowly at first and then rapidly as peak voltage is obtained.

At t = 1 ms, the voltage across the x-ray tube has increased from 0 to approximately 60,000 V. The x-rays produced at this instant are of relatively low intensity and energy; none exceeds 60 keV.

At t = 2 ms, the tube voltage has increased to approximately 80,000 V and is rapidly approaching its peak value.

At t = 4 ms, the maximum tube voltage is obtained, and the maximum energy and intensity of x-ray emission are produced. For the following one quarter cycle between 4 and 8 ms, the x-ray quantity and quality decrease again to zero.

References

- Bushong S. C., . (2017). *Radiologic science for technologists*. St. Louis, Missouri: Elsevier.
- Guy C. and Ffytche D. (2005). *An Introduction to The Principles of Medical Imaging*. Imperial College Press