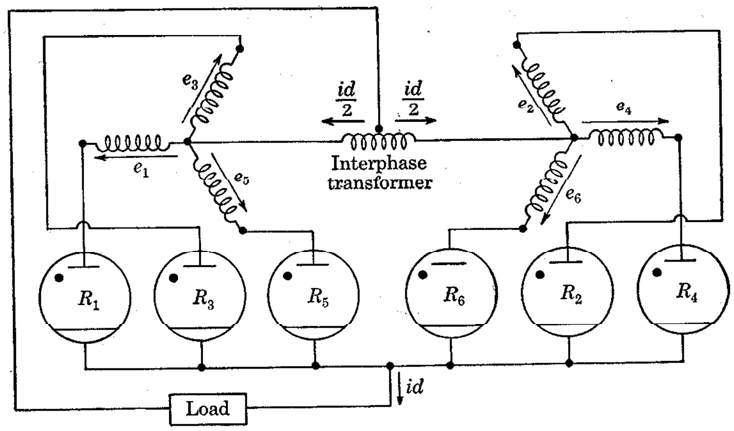
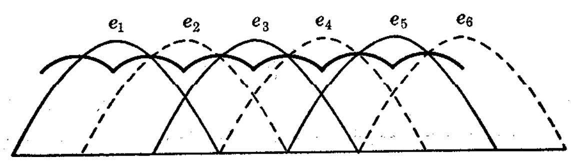
4th edition, 1953, by Lawrence and Richards

Six-phase Double-Y Connection with Interphase Transformer. Three transformers with their secondaries connected in double-Y (see page 134) may be used to supply six-phase power to a six-anode mercury-arc



(a)



(b)

Fig. 344.

power rectifier. The most generally used circuit for mercury-arc power rectifiers however is a modification of the double-Y connection and is the circuit shown in Fig. 344*a*. In this circuit the three primary windings are commonly connected in delta and the neutrals of the two Y-connected secondaries are connected through a center-tapped interphase transformer. The interphase transformer is an iron-core transformer, its only winding being the center-tapped winding shown in the figure. It causes the load current to divide equally between the two Y-connected secondaries. This connection is therefore sometimes called a "double three-phase" rather than a six-phase circuit.

Figure 344*b* shows the positive halves of the voltage waves from neutral to line on the six transformer secondary windings, one group of

Y voltages being shown by full lines, the other group by dotted lines. If current should build up faster in one-half of the interphase transformer winding than in the other half, a voltage is produced by the resulting increasing flux; this voltage opposes the larger current and aids the smaller. This tends to equalize the voltages of the two anodes having the highest positive potentials so that both anodes conduct current. Neglecting the arc-drop, then at each instant of time the load voltage becomes the average of the transformer voltages supplied to the two current-conducting anodes and is shown by the full line of Fig. 344*b*.

Because each half of the d-c current is split among three anodes, the rms value of the anode current equals $I_d/2\sqrt{3}$ for the conditions specified for Eq. (315). The average d-c voltage likewise is that of a three-phase rectifier and under the conditions specified for Eq. (314) equals 0.828 E_m. The ripple frequency however is six times the frequency of the source voltage as may be seen by reference to Fig. 344*b*. This corresponds to the ripple frequency of a six-phase rectifier.

With a very light load connected across the rectifier terminals, the interphase transformer becomes inoperative and the average voltage appearing at the d-c terminals is that of a six-phase rectifier. This voltage under the conditions of Eq. (314) equals 0.956 E_m. As the load current is increased to about 1 per cent of its full load value, the interphase transformer becomes fully magnetized causing the voltage to drop to that of a three-phase rectifier which has an average value of $0.828E_m$ as noted above.

Overlap. The d-c voltage of a mercury-arc rectifier is given by Eq. (314), page 585, if the arc-drop is neglected and conditions are such that there is no overlap and no time delay. Because of the reactance of the windings of the supply transformers however the current supplied to any one anode is not immediately interrupted when the voltage of the next anode becomes slightly higher. The inductance in the transformer circuits causes the currents in one anode to decrease gradually to zero while the current of the succeeding anode gradually builds up to a value equal to the d-c load current as indicated in Fig. 345*b*. The time required for the current to transfer completely from one anode to the next is called the angle of overlap or the commutation angle and is a function of the d-c load current and the inductance in the transformer circuits. The effect of this overlap is to decrease the rms value of the anode current and to decrease the d-c output voltage of the rectifier. The full lines of Fig. 345*a* show the resulting d-c voltage when the commutation angle is taken into account. A comparison of Figs. 343 and 345 shows that the d-c voltage of Eq. (314), page 585, is reduced because of overlap by an amount E_x equal to one-half the shaded area of Fig. 345*a* divided by the

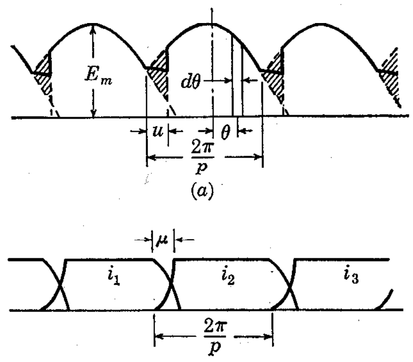


Fig. 345.

base $2\pi/p$ or

$$E_x = \frac{\frac{1}{2}\int_{-\pi/p}^{\mu-\pi/p}\left[E_m \cos\theta - E_m \cos\left(\theta + \frac{2\pi}{p}\right)\right] d\theta}{2\pi/p}$$

$$= \frac{E_m \sin \pi/p}{2\pi/p}(1 - \cos\mu)$$

$$= E_{do}\frac{1-\cos\mu}{2} = E_{do}\sin^2\frac{\mu}{2} \qquad (316)$$

Phase Control or Time Delay. The beginning of the transfer of current from one anode to the next succeeding anode can be delayed beyond the point where the voltages of the two anodes are equal. This is accomplished in multianode rectifiers by grid control and in ignitron

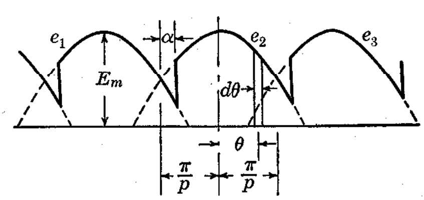


Fig. 346.

rectifiers by delaying the time of supplying the pulse currents to the ignitors. In either case this is referred to as phase control or time delay. The angle by which the beginning of current transfer lags the point of equal voltages is the angle of retard and is shown in Fig. 346 as the angle α. The full lines of this figure show the d-c voltage when time delay is taken into account but the arc-drop and commutation angle are neglected. The average value of this d-c voltage is

$$E'_{d0} = \frac{1}{2\pi/p}\left[\int_{-\pi/p}^{\alpha-\pi/p} e_1\,d\theta + \int_{\alpha-\pi/p}^{\pi/p} e_2\,d\theta\right]$$
$$= \frac{1}{2\pi/p}\left[\int_{-\pi/p}^{\alpha-\pi/p} E_m \cos\left(\theta + \frac{2\pi}{p}\right)d\theta + \int_{\alpha-\pi/p}^{\pi/p} E_m \cos\theta\,d\theta\right]$$
$$= \frac{E_m \sin \pi/p}{\pi/p}\cos\alpha = E_{d0}\cos\alpha \tag{317}$$

Voltage Regulation. It has been shown that the d-c voltage of a loaded mercury-arc rectifier is less than the theoretical value given by Eq. (314) because of the arc-drop, overlap, and phase control. The d-c voltage is further reduced because of the voltage drops in the resistances of the windings of the transformers. This further decrease in voltage equals

$$E_r = \frac{P_r}{I_d} \tag{318}$$

where P_r is the resistance loss in the transformers and I_d is the direct current in the output circuit.

The net d-c voltage taking into account all the above factors is

$$E_d = E_{d0}\cos\alpha - E_a - E_x - E_r \tag{319}$$

The effects of phase control and arc-drop are nearly independent of the load current, but E_r and E_x are nearly proportional to this current. The voltage regulation curve of a mercury-arc rectifier is therefore a sloping straight line, showing a decrease in voltage as the load is increased.

Although phase control reduces the d-c voltage, it is often used as a means of maintaining a more nearly constant voltage at the load. If the angle of retard is decreased when the load is increased, the decrease in voltage due to overlap and resistance drop may be compensated for.

Summary. The only moving parts in a mercury-arc rectifier installation are the pumps required for circulating water for cooling and, in the case of the pumped-type rectifiers, the vacuum pumps. The vacuum pumping system most commonly employed consists of a mercury-vapor diffusion pump without moving parts and a rotary vacuum pump.

The efficiency of a mercury-arc rectifier unit is the ratio of the d-c power output to the power input to the supplying transformers. The losses of the unit therefore consist of the transformer losses, the arc-drop loss, and the power required for operation of the auxiliaries. Because the arc-drop loss is nearly independent of the rectifier voltage, improved efficiency is obtained as the operating voltage is increased. For 600-volt d-c operation, the efficiency of the ignitron-type mercury-arc rectifier is generally higher than that of a synchronous converter throughout the normal load range and the comparison is particularly favorable to the mercury-arc rectifier at light loads.

There are several rectifier circuits other than those discussed in this chapter which are of considerable importance. Included in these are circuits for 12-phase operation and double-way circuits. In the double way circuits, each transformer secondary terminal is connected to two rectifying elements. It is connected to the anode terminal of one element and to the cathode terminal of the other. This nearly doubles the output voltage obtained from a given transformer connection and is most advantageous in the higher voltage ratings.

from Scott-connected transformers or from some other unsymmetrical system, the voltages cannot contain third harmonics.

The wave forms of the three-phase voltages are plotted in Fig. 78 for the case where the two-phase voltages contain 30 per cent third harmonics. The angles α_1 and α_3 are assumed to be 0 and 180 deg. The fundamentals and the third harmonics of each wave are shown dotted.

Three-phase to Six-phase Transformation. *Double Δ and Double Y.* A six-phase system can be derived from any three-phase system by the use of three single-phase transformers, each provided with two independent secondary windings. The primaries can be connected for three phase in either Y or Δ. They should not be connected in Y unless the

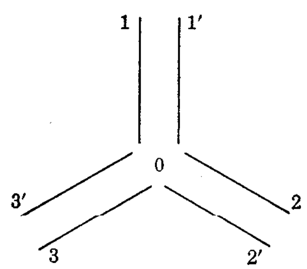


Fig. 79.

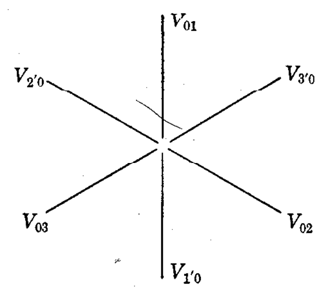


Fig. 80.

secondaries are connected in Δ to give a closed path for the third harmonic of the exciting current which is suppressed in the primaries by Y, connection. The two sets of secondaries are connected to form two independent three-phase systems with the connections of one set of secondaries reversed with respect to the connections of the other set.

The phase relations of the six secondary voltages are shown in Fig. 79. Reversing one group of secondaries gives the phase relations of Fig. 80.

The two groups of secondaries can be connected in Δ or in Y, giving what is known as the double-Δ or the double-Y connection. In either the double-Δ or the double-Y connection, one-half the power delivered by the transformers is supplied by each group of secondaries at three-phase voltage. The connections with the secondaries in double Δ and the primaries in Y are shown in Fig. 81. Figure 82 shows the connections for the secondaries in double Y and the primaries in Δ.

The two Δ's forming the double-Δ secondaries in Fig. 81 have no electrical connection and cannot be considered to form a true six-phase system. However when the secondaries are connected to the armature of a motor or a synchronous converter, the electrical connection between the two Δ's is established and the effect is the same as if six-phase power were fed to the machine. The two Y's forming the double Y can be interconnected at their neutral points n and n' and form under this condition a true six-phase star system.

Diametrical Connection. Three single-phase transformers with single secondaries can be used to supply six-phase power to a synchronous converter or a motor by making use of what is known as the diametrical connection for the secondaries. The diametrical connection is commonly

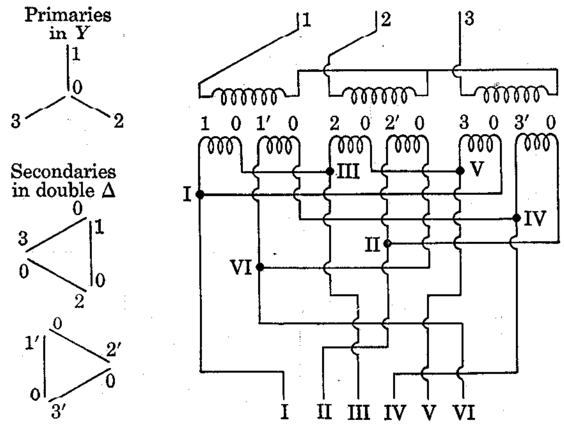


Fig. 81.

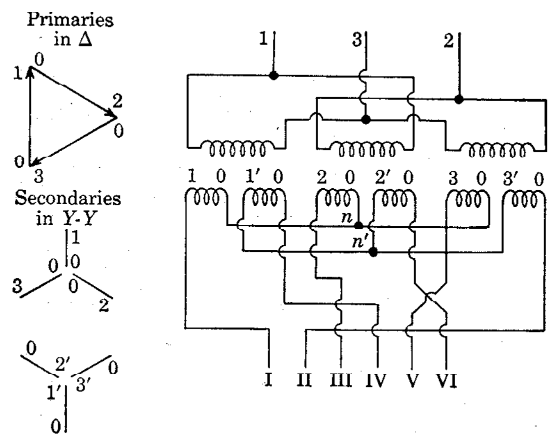


Fig. 82.

employed when synchronous converters are used to supply power for electrical railways. The double-Y connection is always used when a neutral is desired for grounding or for the neutral wire of a three-wire d-c system which receives power from a six-phase synchronous converter. The primaries should be connected in Δ when the diametrical connection is used for the secondaries because of the suppression of the third-harmonic components in the exciting currents by Y-connected primaries.

The diagram for the diametrical connection of transformers to feed six-phase power is given in Fig. 83. The hexagon at the bottom represents the armature which is to receive six-phase power.

If taps are brought out from the middle points of each of the three secondaries and these taps are interconnected, the diametrical connection becomes the double Y.

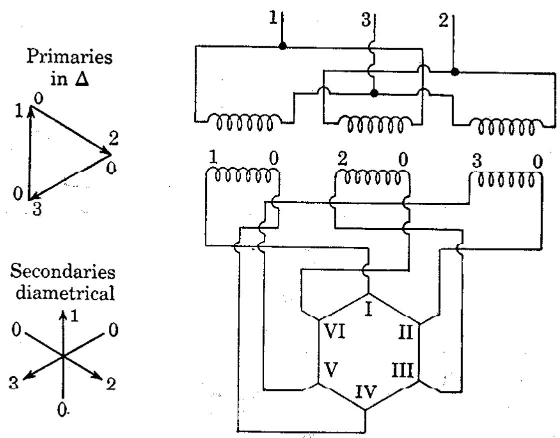


Fig. 83.

Two-phase or Four-phase to Six-phase Transformation. Two-phase or four-phase to six-phase transformation can be accomplished by use of double-T connection on the secondary side of Scott transformers. The connections for this are shown in Fig. 84.

The ratio between the primary and secondary voltages should be the same as for the Scott transformers. If the primaries are also connected

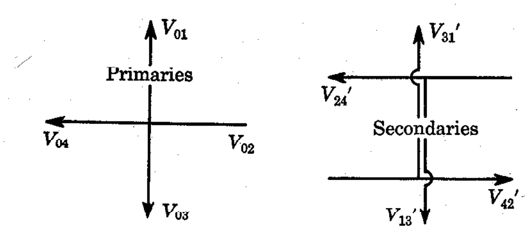


Fig. 84.

in T, the Scott transformers can be used to transform from three phase to six phase.

Interconnected-star or Zigzag Connections. The interconnected-star or zigzag connections can be used to stabilize the neutral when unbalanced loads occur on certain polyphase transformer connections having Y-connected primaries or can be used for deriving multiphase circuits from