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Internal Assessment Test 1 – Sep 2016

Sub:	HVDC Transmission						Code:	10EE751
Date:	07-09-2016	Duration:	90 mins	Max Marks:	50	Sem: 7	Branch:	EEE

Note: **Answer any five full questions. Sketch figures wherever necessary.**

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1. a. What are the different kinds of dc links? Explain in brief. 6M

Direct-current links are classified as shown in Figure 2.

The monopolar link has one conductor, usually of negative polarity, and ground or sea return.

The bipolar link has two conductors—one positive, the other negative. Each term[illegible] has two converters of equal rated voltages in series on the dc side. The [illegible] points (junctions between converters) are grounded at one or both ends. I[illegible]n neutrals are grounded, the two poles can operate independently. Normally they operate at equal current; then there is no ground current. In the event of a fault on one conductor, the other conductor with ground return can carry up to half of the rated load.

The rated voltage of a bipolar link is expressed as ± 100 kV, for example, pronounced plus *and* minus 100 kV.

The homopolar link has two or more conductors all having the same polarity, usually negative, and always operates with ground return. In the event of a fault on one conductor, the entire converter is available for connection to the remaining conductor or conductors, which, having some overload capability, can carry more than half of the rated power, and perhaps the whole rated power, at the expense of increased line loss. In a bipolar scheme reconnection of the whole converter to one pole of the line is more complicated and is usually not feasible because of graded insulation. In this respect a homopolar line is preferable to a bipolar line in cases where continual ground current is

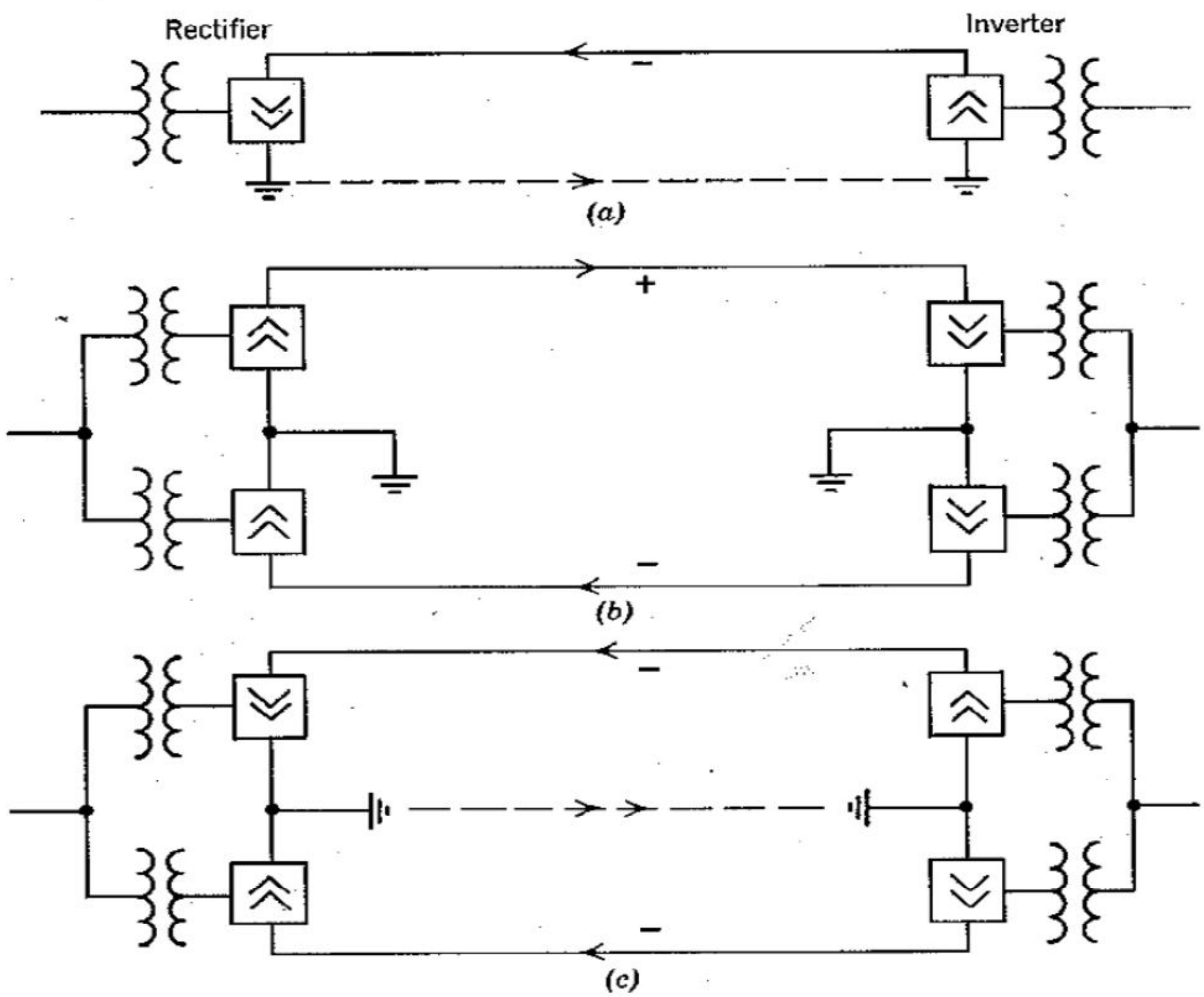

Fig. 2. Kinds of dc links.

not deemed objectionable (see Chapter 9). An additional minor advantage is the lower power loss due to corona. Negative polarity is preferred on overhead lines because of its smaller radio interference.

b. List the major problems in HVAC systems. 4M

1. Current limit
2. Voltage limit
3. Reactive power and voltage regulation
4. Stability
5. Circuit breakers
6. Short circuit current

2. a. Describe a typical HVDC converter station and mention the functions of each element. 6M

b. Compare HVAC and HVDC transmission systems with respect to 4M

(v) Generating units

(vi) Power per conductor per circuit

Some hydroelectric generating stations connected to a load center through long ac lines have generators with abnormally low transient reactance or abnormally high moment of inertia specified in order to raise the stability limit. These features raise the cost of the generators and would not be required if dc transmission were used, for there would be no stability problem with direct current. In addition, if such a station were connected to an ac system only through dc lines, the speed of the prime movers could be allowed to vary with the load or the head of water, perhaps giving a cheaper or a more efficient prime mover, and the nominal frequency of the generator, no longer confined to 50 or 60 Hz, could be chosen for best economy. Perhaps also, in

such a station, less harmonic filtering would be required. (The Volgograd hydroelectric plant has no filters.) Altogether, the generating plant could be designed for best economy. To date, however, no such plant has been built.

Let us assume that an ac line and a dc line using the same conductors and insulators are built. How does the power per conductor compare on the two lines?

Assume that in each case the current is limited by temperature rise. Then the direct current equals the rms alternating current.

Assume also that the insulators withstand the same crest voltage to ground in each case. Then the direct voltage is $\sqrt{2}$ times the rms alternating voltage.

The dc power per conductor is

$$p_d = V_d I_d \tag{9}$$

and the ac power per conductor is

$$p_a = V_a I_a \cos\phi \tag{10}$$

where I_d and I_a are the curents per conductor, V_d and V_a the conductor-to-ground voltages, and $\cos\phi$ the power factor. The ratio is

$$\frac{p_d}{p_a} = \frac{V_d I_d}{V_a I_a \cos\phi} = \frac{V_d}{V_a}\cdot\frac{I_d}{I_a}\cdot\frac{1}{\cos\phi} = \frac{\sqrt{2}}{\cos\phi} \tag{11}$$

Taking $\cos\phi = 0.945$, $p_d/p_a = 1.5$.

Now compare a three-phase, three-conductor ac line with a bipolar two-conductor dc line. The power capabilities of the respective circuits are

$$P_d = 2p_d$$
$$P_a = 3p_a$$

and the ratio is

$$\frac{P_d}{P_a} = \frac{2}{3}\cdot\frac{p_d}{p_a} = \frac{2}{3}\cdot\frac{3}{2} = 1 \tag{12}$$

Both lines can carry the same power. The dc line, however, is simpler and cheaper, having two conductors instead of three. Consequently an overhead line requires only $\frac{2}{3}$ as many insulators, and the towers are simpler, cheaper, and narrower. A narrower right of way could be used.

Both lines have the same power loss per conductor. The percentage loss of the dc line is only two-thirds that of the ac line. If the basis of comparison is equal percentage loss, the power of the three-phase ac line is decreased to $\sqrt{2/3}$ that of the two-conductor dc line.

If cables are used instead of overhead line, the permissible working stress (voltage per unit thickness of insulation) is higher for direct current than for alternating current, and, in addition, the power factor for direct current is unity and, for alternating current, considerably lower than that assumed above. Both changes further favor direct current over alternating current by increasing the ratio of dc power to ac power per conductor. The resulting ratio might be from 5 to 10.

Because the power limit of overhead ac lines is often determined by factors other than conductor heating, the ratio of dc power per conductor to ac power per conductor may be as high as 4.

3. a. Briefly explain the Thury system. 4M

   b. Explain the experimental dc transmission projects and first commercial lines. 6M

A system of HV dc transmission designed by a French engineer, René Thury, came into use at a time when ac systems were in their infancy, and it persisted well into the era of ac predominance. This system is interesting both as an engineering achievement and because of certain similarities to modern HV dc systems. At the sending end of the transmission line a number of series-wound dc generators, driven by prime movers, were connected in series to generate the required high voltage, and at the receiving end, a comparable number of series-wound dc motors, connected in series, drove low-voltage dc or ac generators. The system operated at constant current. The voltage of each machine in the HV series circuit was regulated by shifting the brushes.

Since the series circuit was normally grounded at only one point, many of the machine windings had a high potential with respect to ground. It was not feasible to provide insulation between windings and frame for such voltages; instead, the frames were insulated from ground by setting them in a floor of asphalt over asphalt concrete, and were insulated from the driving or driven machines by insulated couplings.

Switching and instrumentation were very simple. Each machine was provided with a short-circuiting switch. A machine was taken out of service by reducing its terminal voltage to zero and then short-circuiting it. It was brought into service by the reverse of this procedure. An ammeter and a voltmeter were the only instruments required.

From 1880 to 1911 at least 19 Thury systems were installed in Europe, principally for the use of water power. The most important of these was that from Moutiers, in the French Alps, to Lyons,[B3] installed in 1906 with a route length of 112 mi (180 km) of which 2.8 mi (4.5 km) were in underground cable, the remainder being open-wire line. Initially, its rated power of 4.3 MW was transmitted at 57.6 kV, 75 A. This line was built as a reinforcement of an existing ac system and was integrated with it. The Moutiers plant had four water turbines, each driving four generators of 3.6 kV each. At Lyons the greater part of the power received by HV direct current was converted to alternating current and the remainder to 600 V dc for the street railway. The over-all efficiency was 70.5%, which was considered satisfactory for a hydroelectric system.

In 1911 a second hydroelectric plant at La Bridoire, situated about halfway along the line and rated at 6 MW, was added (in series). The line current was then doubled (to 150 A). In 1912 a third hydro plant, located at Bozel, 7 mi (11 km) beyond Moutiers, and rated at 9 MW, was added, raising the total generating capability on the line to 19.3 MW. The maximum circuit voltage became 125 kV and the route length 140 mi (225 km). Operation of the line continued until 1937, when it was dismantled. Thury himself died in 1938.

The Thury system performed reliably in spite of the large number of commutators in series. The limitations of dc machines, already mentioned, however, made it unsuitable to the larger amounts of power that had come to be required. Further development of HV dc transmission required better converters than motor-generator sets.

Experimental DC Transmission Projects and First Commercial Lines

The initiative in exploring the use of mercury-arc valves for dc transmission was taken by the General Electric Company. After two smaller experiments[B1,2] they proceeded in December 1936 to use direct current on a 17-mi (27-km) line between the Mechanicville hydroelectric plant of the New York Power & Light Corporation and the General Electric factory in Schenectady.[B15] The line carried 5.25 MW at 30 kV, 175 A. The converter at each end of the line had 12 hot-cathode glass-envelope thyratrons in 6 series pairs. The ac input at Mechanicville was at a frequency of 40 Hz, and the output at Schenectady was at 60 Hz. Thus was demonstrated a feature of dc transmission that has been important in several subsequent installations: frequency conversion.

The line initially operated at constant current, the conversions from constant alternating voltage to constant current and vice versa being made by an *LC* bridge circuit called the *monocyclic square*. Constant-current operation was chosen because the hot-cathode tubes then used could not withstand the high short-circuit currents expected to occur on a constant-voltage system. After the more rugged steel-envelope mercury-pool ignitron became available, however, the line was converted in 1940 to constant-voltage operation. The circuitry then used was basically the same as that of modern dc transmission systems, fault currents being limited by control of valve ignition. The operation of the line was discontinued in 1945 in the belief that nothing more would be learned by continuing it. Perhaps an additional belief was that there was no future in dc transmission.

4. a. Explain the valve characteristics with symbol for a controlled mercury arc valve. 8M
   b. Write the properties of converter circuits. 2M

2-1 VALVE CHARACTERISTIC

The symbol for a controlled mercury-arc valve is shown in Figure 1*a*. Symbols for uncontrolled and controlled valves of any type (mercury-arc or solid-state) are shown in Figures 1*b* and *c*, respectively.

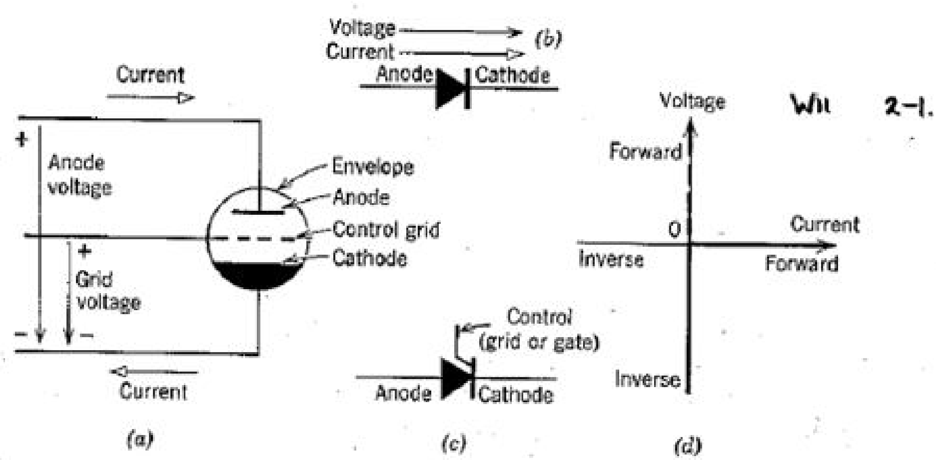

Fig. 1. (*a*) Symbol for mercury-arc valve with control grid; (*b*) symbol for any uncontrolled valve; (*c*) symbol for any controlled valve; (*d*) idealized valve characteristic.

A valve normally conducts in only one direction, from anode to cathode; and while it is conducting there is a small drop of voltage across it. Such current and voltage are in the *forward* direction and are taken as positive. The forward voltage drop in a mercury-arc valve is in the range of 20 to 50 V, the higher values (40 to 50 V) pertaining to HV valves. Barring abnormal operation (arcbacks), the valve can sustain a comparatively high voltage in the negative or *inverse* direction without conducting, except for a negligible leakage current (milliamperes).

The rated current for valves for HV dc may be hundreds or thousands of amperes, and the rated peak inverse voltage, 50 to 150 kV. In comparison, the inverse leakage current and the forward voltage drop are negligible. Hence the idealized voltage-current characteristic of a diode, shown by the solid heavy line in Figure 1*d*, is adequate. It consists of two half-axes:

1. Positive (forward) current at zero voltage
2. Negative (inverse) voltage at zero current

In a valve having a control grid at a sufficiently negative voltage with respect to the cathode, the current is prevented from starting, although the anode may be positive. The valve may then operate on the branch shown as a broken heavy line in Figure 1*d*.

In this chapter, valves are assumed to have no control grids, from which it follows that the converters operate only as rectifiers with no ignition delay. This mode of operation affords a comparison of the various converter circuits that is valid also for rectifier and inverter operation with grid control.

It follows from the characteristics of uncontrolled valves that (1) if the cathodes of several valves are connected together, the common potential of these cathodes is equal to that of the most positive anode, and (2) if the anodes of several valves are connected together, the common potential of these anodes is equal to that of the most negative cathode.

2-2 PROPERTIES OF CONVERTER CIRCUITS

For each circuit considered, we find the wave forms of the voltages and currents and their magnitudes in terms of the direct voltage V_d and direct current I_d. From these data we find the required volt-ampere ratings of valves and transformers in terms of the dc power $P_d = V_d I_d$.

The volt-ampere rating of a valve is taken as the product of its average current and its peak inverse voltage (PIV), and the rating of a transformer winding is the product of its rms voltage and rms current.

5. a. Describe the 3-phae one way rectifier with waveform and obtain the PIV, pulse number and average value of voltage across the valve. 8M

   b. List out the assumptions in converter circuit analysis. 2M

Three-phase One-way Rectifier

This is the simplest three-phase converter circuit (Figure 7). It is not practical as shown, because the direct current in the secondary windings

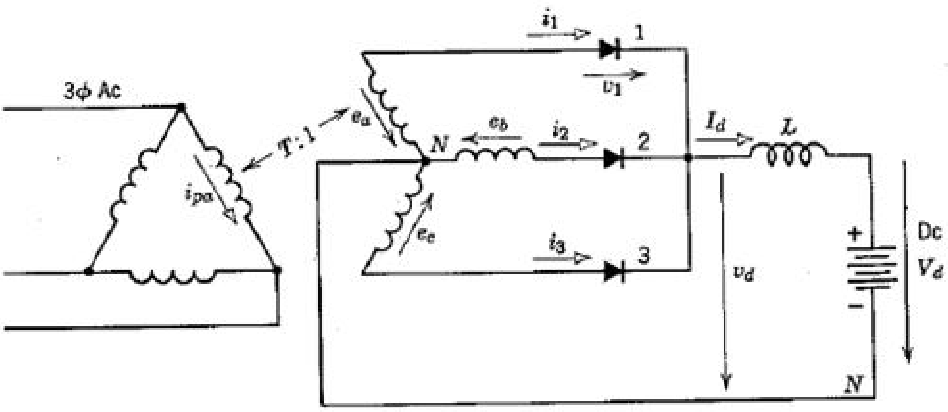

Fig. 7. Three-phase one-way rectifier circuit.

saturates the transformer cores. This may be avoided by replacing the Y connection by the zig-zag connection, in which the dc MMFs of the two secondary windings on the same core cancel out. The circuit as shown, however, is useful as a step in explaining several other connections, and therefore it is analyzed as it stands.

The three secondary voltages e_a, e_b, e_c form a balanced three-phase set, as shown in Figure 8*a*, and the anode voltages with respect to neutral point N are equal to the corresponding secondary voltages. The common cathode voltage v_d coincides with the upper envelope of this set of voltages, as shown by the heavy line. The average direct voltage V_d is given by

$$\frac{V_d}{E_m} = \frac{3}{\pi}\int_0^{\pi/3} \cos\theta \, d\theta = \frac{3}{\pi}\Big(\sin\theta\Big)_0^{\pi/3} = \frac{3}{\pi}\cdot\frac{\sqrt{3}}{2} = 0.828 \qquad (3)$$

whence

$$E_m = 1.209 V_d \qquad (4)$$

The peak-to-peak ripple is

$$E_m(1 - \cos 60°) = \frac{E_m}{2} = 0.605 V_d \qquad (5)$$

with ripple frequency $3f$.

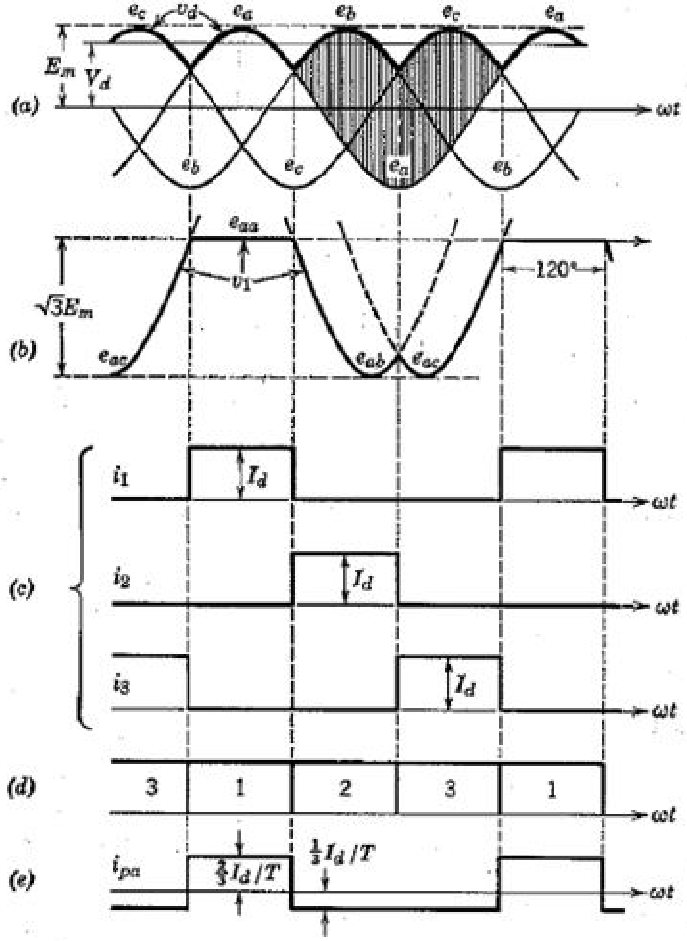

Fig. 8. Wave forms in the circuit of Figure 7. (*a*) secondary voltages, e_a, e_b, e_c, unfiltered direct voltage v_d, and filtered direct voltage V_d; (*b*) voltage v_1 across valve 1; (*c*) valve currents i_1, i_2, i_3, which are also transformer secondary currents; (*d*) condensed representation of valve currents; (*e*) one primary winding current i_{pa}.

The wave form of voltage across valve 1, shown in Figure 8*a* and *b*, consists of three segments, each lasting one-third cycle or 120°. In one segment, while the valve is conducting, the valve voltage is zero; in the other two segments, while the valve is nonconducting, it has an inverse voltage equal to one of the line-to-line voltages, first e_{ab}, then e_{ac}. In Figure 8*a* it is shown by the height of the vertical shading; in Figure 8*b* it is redrawn from a horizontal axis. The P.I.V. is

$$\sqrt{3}E_m = \sqrt{3} \times 1.209V_d = 2.094V_d \tag{6}$$

The transformer secondary voltage has crest value E_m and rms value $E_m/\sqrt{2} = 1.209V_d \times 0.707 = 0.855V_d$.

Each valve conducts during the one-third cycle when the associated secondary voltage is the highest one. The wave of valve current is a rectangular pulse of height I_d and length 120° (Figure 8*c*). Its average value is $I_d/3$, and its rms value is $I_d/\sqrt{3} = 0.577I_d$. The transformer secondary current is the same as the valve current. The primary current (Figure 8*e*) differs from the secondary current in having no dc component; that is, its average value is zero. Its rms value is

$$\frac{I_d}{T}\sqrt{\frac{1}{3}\left(\frac{2}{3}\right)^2 + \frac{2}{3}\left(-\frac{1}{3}\right)^2} = \frac{\sqrt{2}\,I_d}{3T} = \frac{0.471I_d}{T} \tag{7}$$

The aggregate valve rating is

$$3 \times 2.094V_d \times 0.333I_d = 2.094P_d \tag{8}$$

The volt-ampere ratings of the transformer bank are

Secondary: $$3 \times 0.855V_d \times 0.577I_d = 1.481P_d \tag{9}$$

Primary: $$3 \times 0.855TV_d \times \frac{0.471I_d}{T} = 1.209P_d \tag{10}$$

2-3 ASSUMPTIONS

In addition to idealizing the valves, we idealize the ac source, the transformer, and the dc sink (load), as follows:

The ac source has no impedance and delivers constant voltage of sinusoidal wave form and constant frequency. If polyphase, it delivers balanced voltages.

The transformers have no leakage impedance nor exciting admittance.

The dc load has infinite inductance, from which it follows that the direct current is constant, that is, free from ripple. This assumption is justified by the fact that HV dc converters have large dc smoothing reactors (about 1 H), and it is reasonably accurate for converters having six or more pulses per cycle, as those used for HV dc transmission have, although it is a poor assumption for single-phase converters. Although the current is assumed free from ripple, the direct voltage on the valve side of the smoothing reactor has ripple. The dc load is shown on our circuit diagrams as a reactor in series with an EMF of constant voltage, which is equal to the *average* value of the ripply voltage on the valve side of the reactor.

6. a. "The Best converter circuit for HVDC transmission is 3 phase bridge". Justify the statement by explaining its advantages. 6M

   b. Explain Cascade of three single-phase full-wave rectifiers circuit. 4M

1. For a given direct voltage, the P.I.V. of the valves is only half that of any of the other six-pulse circuits except 5 and 8, in which it is equal. Consequently for a given P.I.V., the direct voltage is twice that of some other circuits.

2. For a given power throughput, the volt-ampere rating of the transformer secondary winding is less than that in any other circuit.

3. The volt-ampere rating of the transformer primary windings is equal to or less than that of the other circuits.

4. The transformer connections are the simplest. Double or center-tapped secondary windings are not required. This simplcity is important for obtaining a sturdy and reliable design for operation at very high voltages having superposed high-frequency transient voltages caused by commutation.

5. The secondary windings may be connected either in Y or in Δ. The advantages of this will appear in Section 2-9.

6. The aggregate volt-ampere rating of the valves is lower than that of circuit 8 and equal to that of the rest.

7. A very important property of the bridge circuit is that arcbacks* can be suppressed by grid control and a bypass valve. Arcback is a random phenomenon that is unlikely to occur in more than one valve at the same time. Thus, although grid control is ineffective in the valve with the arcback, it may reasonably be expected that in all other valves of the same bridge such control will be effective and may be used to prevent any of these valves from reigniting after the current in them has once become zero. In the bridge connection there are two valves in series across the dc line and two in series opposition across each pair of ac terminals. If all valves but the maloperating one are blocked by grid control, that one has no circuit through which current can be furnished to it. This is in contrast to the six-phase star and Y-Y-interphase connections, in which there is a path through the ac source, the maloperating valve, and the dc load.

Because of these advantages, the bridge circuit is universally used for high-power HV ac-dc converters.

Cascade of Three Single-phase Full-wave Rectifiers

At first sight it appears that this circuit (Figure 14) might give a higher direct voltage for a given P.I.V. on the valves than either the bridge circuit or the cascade of two three-phase rectifiers, but it does not. Moreover, the transformer utilization is poor.

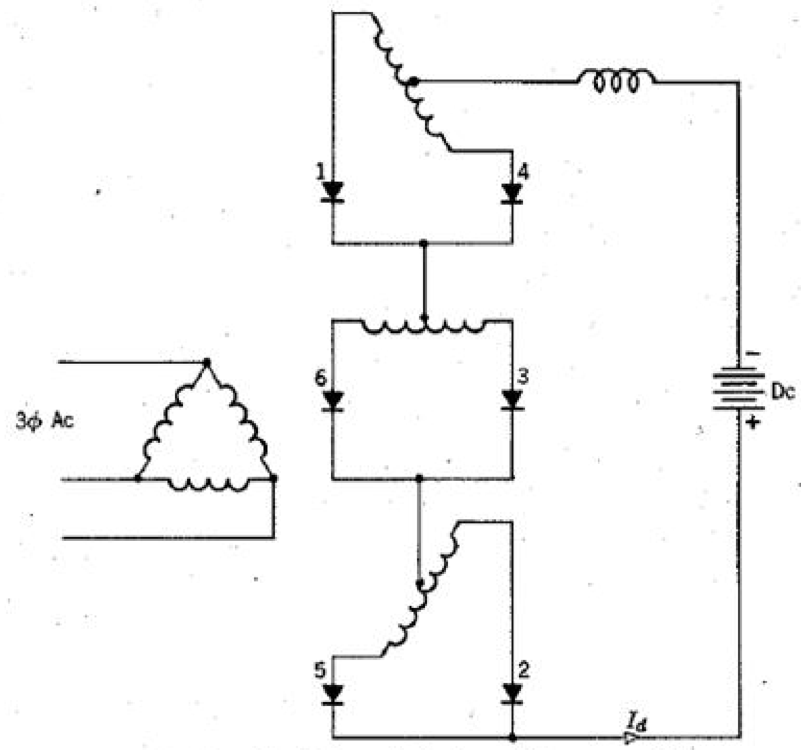

Fig. 14. Cascade of three single-phase full-wave rectifiers.

7. Explain the Graetz circuit , with waveforms and obtain 10M
   - (vi) Average of direct voltage
   - (vii) peak to peak voltage ripple
   - (viii) PIV
   - (ix) Aggregate valve rating
   - (x) VA rating of transformer primary and secondary

Three-phase Two-way, or Three-phase Bridge Rectifier

This is known in Europe as the *Graetz circuit* (Figure 9). In the circuit in Figure 7, if the three valves are reversed, the circuit operates as before except that the directions of direct current and direct voltage are reversed. The same transformer secondary windings may feed two groups of three valves each, one group connected as in Figure 7, the other connected similarly except for reversal of the valves. Each group may feed a separate dc load, the two loads constituting a three-wire load with its neutral point connected to the transformer neutral. Now, if the two loads have equal currents, the neutral conductor carries no current and may be omitted. Since the neutral point of the

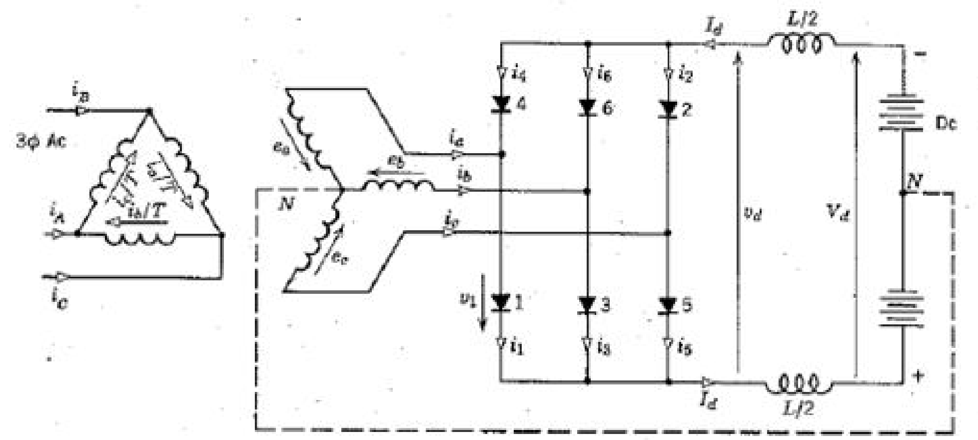

Fig. 9. Three-phase two-way, three-phase bridge, or Graetz rectifier circuit.

transformer windings is no longer necessary, those windings can be connected in Δ instead of in Y if desired. The Y connection is shown in Figure 9.

The relation between the three-phase single-way and two-way circuits (Figures 7 and 9) is like that between the single-phase single-way and two-way circuits (Figures 3 and 5). Again, for a given alternating voltage, the direct voltage and power are doubled, but the P.I.V. is not altered. In terms of V_d, it is halved and becomes $1.047V_d$. This makes the circuit advantageous if high direct voltage and high power are required.

Other advantages appear in the transformer bank. There is no direct current in the windings, and the rms current is less than twice that of the single-way connection, giving more efficient use of the windings.

The wave forms are shown in Figure 10. The transformer secondary line-to-neutral voltages are shown in Figure 10*a*. These are also the voltages of the anodes of the lower group of valves and of the cathodes of the upper group, all with respect to neutral point *N*. The common cathode voltage of the lower group of valves is the upper envelope of the transformer voltages, as it was for the single-way circuit in Figure 7. The common anode voltage of the upper group of valves is the lower envelope. The difference in ordinates between the upper and lower envelopes is the instantaneous direct voltage v_d on the valve side of the smoothing reactor. This is replotted in Figure 10*b* as the envelope of the line-to-line voltages. The voltage across valve 1 is also shown (Figure 10*c*).

It is immediately to be noted that the ripple of the direct voltage is of frequency $6f$, twice that of the one-way connection, and the magnitude of the ripple is smaller. The reason is that the scallops of the lower envelope are shifted one-sixth cycle from those of the upper envelope.

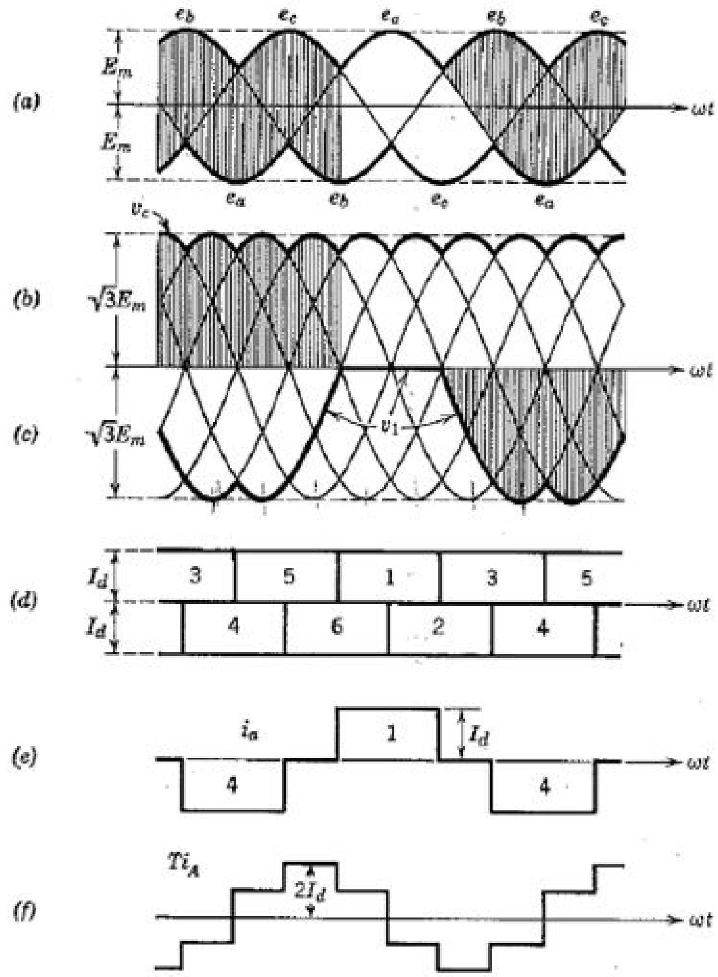

Fig. 10. Wave forms of the circuit of Figure 9: (*a*) secondary line-to-neutral voltages e_a e_b, e_c and, in heavy lines, unfiltered voltages of positive and negative dc poles with respect to transformer neutral point; (*b*) secondary line-to-line voltages and, in heavy line, unfiltered direct pole-to-pole voltage v_d; (*c*) secondary line-to-line voltages and, in lower heavy line, voltage v_1 across valve 1; (*d*) condensed representation of valve currents; (*e*) transformer secondary current $i_a = i_1 - i_4$; (*f*) primary alternating line current $i_A = (i_c - i_b)/T$.

The average direct voltage V_d is given by

$$\frac{V_d}{\sqrt{3}E_m} = \frac{6}{\pi}\int_0^{\pi/6} \cos\theta\, d\theta = \frac{6}{\pi}\left(\sin\theta\right)_0^{\pi/6} = \frac{6}{\pi}\cdot\frac{1}{2} = \frac{3}{\pi} \qquad (11)$$

whence the P.I.V. is

$$\sqrt{3}E_m = \frac{\pi}{3} V_d = 1.047 V_d \qquad (12)$$

The peak-to-peak ripple is

$$(1 - \cos 30°)\sqrt{3}\,E_m = 0.134 \times 1.047V_d = 0.140V_d \tag{13}$$

The rms line-to-neutral secondary voltage is

$$0.707E_m = 0.707 \times \frac{1.047V_d}{\sqrt{3}} = 0.428V_d.$$

The load current is always carried by two valves in series, one from the upper half bridge and one from the lower. Each valve conducts for one-third cycle, as in the one-way circuit. Commutation in one group, however, is staggered with respect to commutation in the other group; considering both groups, commutation occurs every one-sixth cycle (60°). In Figure 9, as well as in the diagrams of other converter circuits, the valves are numbered in the order in which they fire (begin to conduct). Commutation occurs from valve 1 to valve 3, then from 2 to 4, from 3 to 5, from 4 to 6, from 5 to 1, and from 6 to 2. The current wave forms are shown in condensed fashion in Figure 10*d*.

The current in each phase of the Y-connected secondary windings is the difference of the currents of two valves, the numbers of which differ by 3; for example, $i_a = i_1 - i_4$ (Figure 10*e*). Its rms value is $I_d\sqrt{2/3} = 0.816I_d$.

The aggregate valve rating is $6 \times 1.047V_d \times I_d/3 = 2.094P_d$.

The aggregate volt-ampere rating of the transformer secondary windings is $3 \times 0.428V_d \times 0.816I_d = 1.047P_d$. The rating of the primary windings is the same as that of the secondaries.

If the secondary windings are connected in Δ instead of Y, the wave shape of current is different (Figure 10*f*), and its rms value is $1/\sqrt{3}$ times that of current in the Y. The primary line currents have the same wave shape as secondary Y currents if the transformer connection is YY or ΔΔ, and the same wave shape as secondary Δ currents if the transformer connection is ΔY or YΔ.