The Direct-current Transformer Utilizing Thyratron Tubes

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The transformation of direct current without rotating machinery has for many years afforded a most fascinating problem. Starting with the already available tube rectifier as the latter half of a dc-ac./ac-dc. transformation, pliotrons were a few years ago made to function as inverters and thus complete the solution. In power applications, however, thyratrons are more suitable than pliotrons. —EDITOR

IN a previous article describing the Inverter[1] it was shown that pliotrons, or high-vacuum three-electrode valves, in suitable circuit arrangements can be made to convert direct current into alternating current in a manner the inverse of that in which a rectifier converts alternating current to direct current. In developing the inverter, the transfer or commutating problem was solved in such a way that the current reverses naturally, leaving to the pliotron grid only the function of holding the current at zero until it should flow again.

The inverter is particularly well adapted for converting direct-current power into alternating-current power at the usual commercial frequencies except for the losses that result from the present rather high space charge drop in the pliotrons. In recent years considerable research by several workers has been undertaken in order to produce and utilize tubes without incurring excessive losses. One of the most interesting of these tubes is the "Thyratron," one form of which consists of a mercury-arc rectifier with a grid added to each anode arm, as shown in Figs. 1 and 2. In operation, the low voltage drop and high efficiency of the mercury-arc rectifier are obtained with valuable control characteristics which are, however, somewhat different from those of the pliotron. While no current is flowing to an anode, the space surrounding that anode remains free of ionization. In this state, the well-known laws of grid action apply as in a high-vacuum tube. As long as the negative electric field due to the grid predominates over the positive electric field due to the anode, no current will flow. If, on the other hand, current is flowing to the anode, the surrounding space is filled with ionization and the grid is no longer effective. The thyratron thus has the characteristic that current can be prevented from starting by a small negative grid voltage but cannot be stopped under the usual conditions of operation by applying a large negative grid voltage. These tubes are, therefore, not suitable for driving oscillating circuits unless a natural stopping of the current is obtained by such methods as was described in the article on inverters.[1]

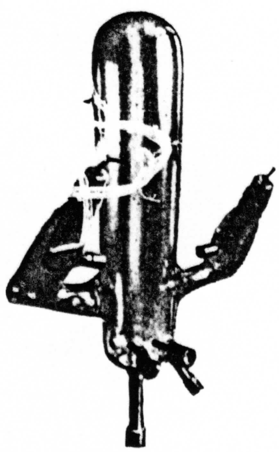

Fig. 1. Thyratron Tube

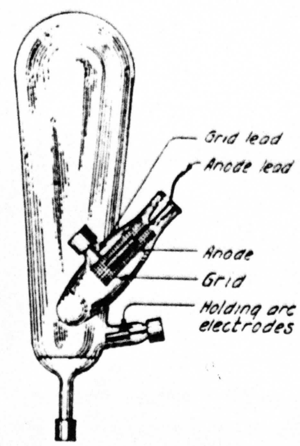

Fig. 2. Sketch of Thyratron Tube with Principal Parts Indicated

More specifically, the current flow is stopped without using grid control. Such a circuit is shown in Fig. 3. It differs from a single-phase high-vacuum tube inverter circuit in that no attempt need be made to keep the grid current proportional to the anode current. As in the high-vacuum inverter, an angular advance must be given to the grid phase. The operation of such a circuit is indicated in Fig. 4. In this

[1] "The Inverter," by D. C. Prince, GENERAL ELECTRIC REVIEW, October, 1925, p. 676.

illustration, the center points of the transformer windings are used as the points of voltage reference. The potentials e_{a1} and e_{a2} are impressed upon the two anodes a_1 and a_2. Between times t_1 and t_1', the potential of grid g_1 is positive so that current flows to it and to the anode a_1 that it surrounds. During this time, grid g_2 has a negative potential impressed upon it so that no current can start to flow to a_2, the anode which it surrounds.

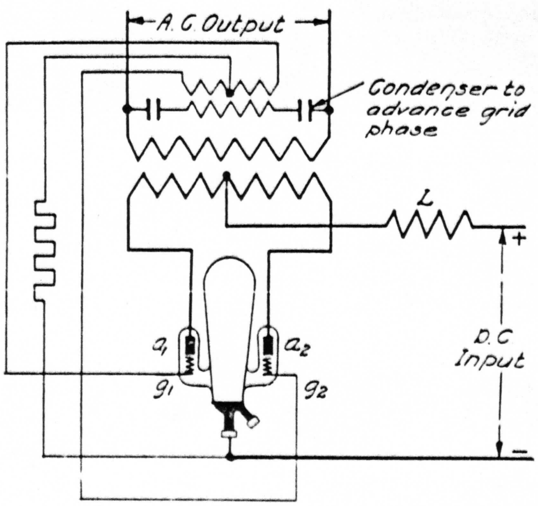

Fig. 3. Thyratron Inverter Circuit

At t_1' the relative polarity of the grids reverses. At this time, anode a_2 is more positive than a_1, and therefore tends to gain current at the expense of a_1 since the total current is held substantially constant by inductance L. Between t_1' and t_2', all the current leaves anode a_1 for a_2 so that at t_2' there is nothing to maintain ionization in the neighborhood of grid g_1 and anode a_1. From t_2' to t_3', the ionization decays and the grid g_1 is able to prevent the current from restarting when anode a_1 becomes more positive than a_2 at t_3'.

At t_1'' the reverse transfer begins to take place and is completed by t_2'', the time between t_2'' and t_3'' serving for de-ionization of the space around a_2.

The wave form of voltage is here assumed to be supplied by the load which may be synchronous machinery or may include static condensers. The operation with static condensers is described in greater detail later.

For purposes of reference, the diagram of a single-phase rectifier is shown in Fig. 5, and the corresponding wave shapes in Fig. 6. A comparison will show a great similarity between the connection diagrams and wave shapes of the inverter and the rectifier. Except during transfer, the inverter and the rectifier have sine waves of counter-voltage and of voltage respectively. Each has a nearly square current wave. The instantaneous powers of the two are therefore of the same form. The variations from the average are absorbed by the inductances and are also of the same form.

It is therefore possible to combine the two circuits as in Fig. 7. In the combination, the alternating-voltage wave form is supplied by condenser C which supplies the transformer excitation that is purposely made large for stability. Since the inverter input power has the same form as the rectifier output power, there is no need for any energy to be stored inside the device except that represented by transformer excitation. That is, the input and output currents neutralize and do not tend to prevent the free swing of the oscillating excitation circuit which acts as a small flywheel. If the power input and output did not balance, a large flywheel would be required, but with the nearly perfect balance very little storage action is necessary.

Since the departures from average power are similar in both inverter and rectifier, the inductances L_1 and L_2 may be wound on the same core provided the turns are in the same ratio as the turns of the main transformer. Were separate inductances used, each would carry a direct-current component and so would have to be made with open cores. When combined on a

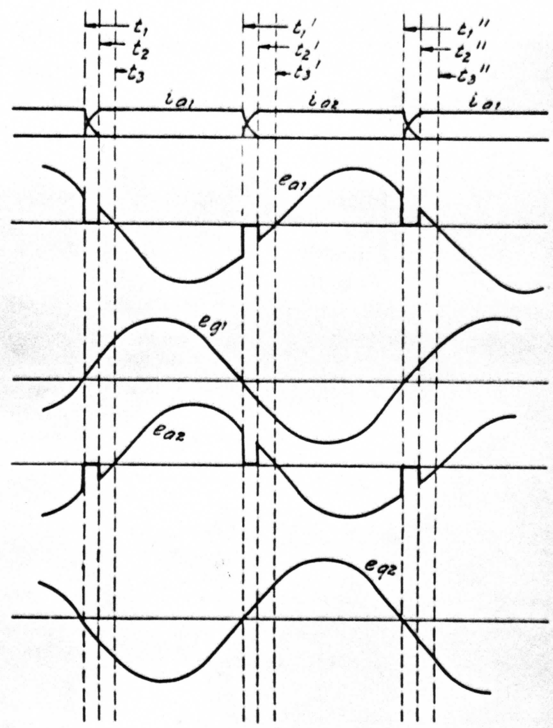

Fig. 4. Wave Shapes of Thyratron Inverter, Showing the Transfer of Current Advanced in Phase with Respect to t_3, t_3', t_3'', etc.

i_{a1} and i_{a2} are the anode currents; e_{a1} and e_{a2} are the anode voltages with respect to the middle of the transformer primary winding; and e_{g1} and e_{g2} are the grid voltages with respect to the center of the winding supplying grid excitation.

single core, however, the inverter and rectifier direct currents flow in opposite directions in this two-circuit inductance, so that the saturating effects cancel and a closed core can be used.

Such a closed core does not store energy as does a heavy inductance. Instead, a sudden rise of rectified load accompanied by a corresponding rise in inverter input encounters only the leakage reactance of the combination reactance. When the oscillating circuit voltage is passing through zero, the inverter has no counter-electromotive force, and the entire impressed voltage appears across the inductance. Simultaneously the rectifier has no output voltage so that the entire load must be supplied by the inductance. This device, therefore, transfers power directly from input to output circuits. Conversely, when the oscillating voltage is at its peak, it is higher than the impressed continuous potential. Simultaneously, the rectifier voltage is higher than the counter-electromotive force of its load circuit, so that energy flows back from the rectifier to the inverter circuit.

In effect, the main transformer converts the fundamental energy in sine waves. The combination reactance converts the harmonic energy difference between

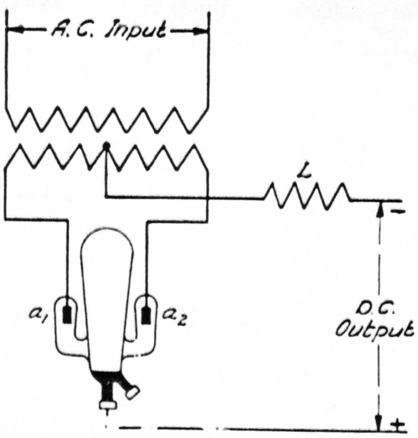

Fig. 5. Mercury Arc Rectifier Circuit

the continuous input and output and the pulsating energy of the main transformer. The title of harmonic transformer would seem to apply naturally to this piece of apparatus.

Turning now to the transfer period as shown in Fig. 8, it appears that from t_2 to t_2' the potential difference between inverter anodes a_1 and a_2 is in the correct direction to produce transfer to a_2. At t_1', grid g_2 becomes positive and current can flow to anode a_2. Condenser C promptly discharges, throwing the current all to anode a_2. From t_1' to t_2', the current to anode a_1 is held at zero by the continuing discharge of condenser C which is, however, hastened by the fact that the current is not commutated immediately by the transformer and must, therefore, pass through C until the secondary current is commutated. De-ionization of the space surrounding anode a_1 takes place during this period.

The potential difference between anodes a_1 and a_2 reverses at t_2', but de-ionization is complete and grid g_1 now has a negative potential so that the current cannot return to anode a_1. The potential difference is now correct to transfer current from rectifier anode a_3 to a_4. This transfer takes place between t_2' and t_3', and the free oscillation cycle then recommences. Between t_1 and t_2 and between t_1' and t_2', etc., full-load current flows in condenser C; and even after t_2 and t_2', part of the load current flows through C for a short period.

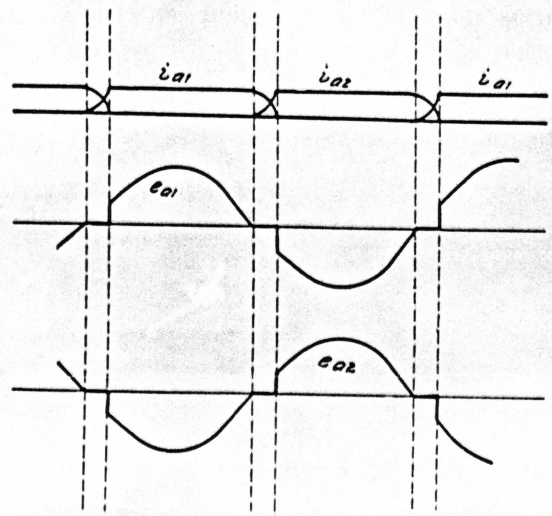

Fig. 6. Mercury Arc Rectifier Wave Forms, Showing Natural Lag of Current Transfer

i_{a1} and i_{a2} are the anode currents; and e_{a1} and e_{a2} are the anode voltages with respect to the middle of the transformer secondary winding.

Fig. 9 shows oscillograms of some of the currents and voltages in different parts of the circuit. Unfortunately, sufficient vibrators were not available so that all traces could be made on one film. Fig. 9 therefore consists of two films. Due to slight irregularities, it was impossible to match these films exactly, but the upright lines are drawn through corresponding points on the various traces. Trace a is the potential between one thyratron anode and the cathode. Trace b shows the corresponding anode current. This trace was taken through a current transformer so that trace b_0, the normal zero line, is in reality the average direct current; and the

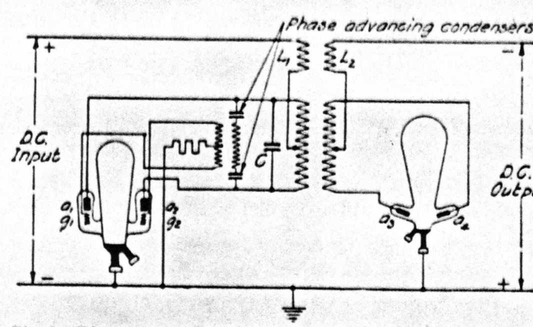

Fig. 7. Direct-current Transformer Circuit, Showing the Combination of Rectifier Circuit (Fig. 5, on right) and Inverter Circuit (Fig. 3, on left)

A small oscillating circuit including condenser C and the exciting reactance of the transformer shown to the right of it supplies the exciting current for this transformer and stores the small amount of energy required for this service.

true zero line b' must be drawn on the film. The current is zero while there is a drop across the tube and, when it starts, it jumps to full value while the voltage falls to almost nothing. This accounts for the very high efficiency of these devices, since losses require simultaneous current and voltage drop. Trace c shows the current drawn by one grid. The starting of the grid and the anode currents coincide, but, unlike the high-vacuum tube, no further correspondence is necessary. This contributes to the simplicity of circuit design, since no provisions for controlling the grid-current wave shape are required. Trace d is the main transformer secondary voltage. Each half cycle shows the usual form of a shock-excited wave with a fairly high decrement. This decrement is probably due mostly to the alternating-current losses, since the output is almost exactly balanced by the input throughout the cycle. Trace e is the voltage across the grid transformer. It leads the main transformer voltage in time.

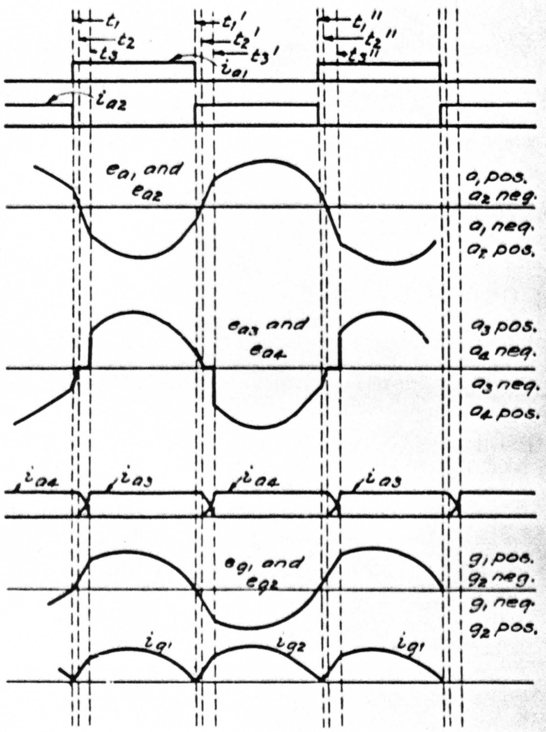

Fig. 8. Wave Shapes of Direct-current Transformer, Indicating the Combination of Those Corresponding to the Inverter and the Rectifier

i_{a1} and i_{a2} are the thyratron anode currents, e_{a1} and e_{a2} the thyratron anode voltages with respect to the middle of the transformer winding. i_{a3} and i_{a4}, and e_{a3} and e_{a4} are the anode currents and voltages of the rectifier. e_{g1} and e_{g2} are the thyratron grid voltages with respect to the mid-point of the exciting winding and i_{g1} and i_{g2} the grid currents.

It will be observed that the time t_1 at which the grid voltage reverses is the time at which a sudden change takes place in each of the other waves. These rapid changes are due to the release of the condenser charge for an instant during which it commutates the inverter current. This is started by the grid which becomes positive, and it stops when commutation is completed. Since there is no reactance in the circuit involved, the action is extremely rapid. At time t_2, the reverse action takes place. A point of particular interest is the negative kick in trace a. This is due to commutating the inverter current before the voltage passes through zero, and is depended upon to stop the arc and allow the grid to acquire control.

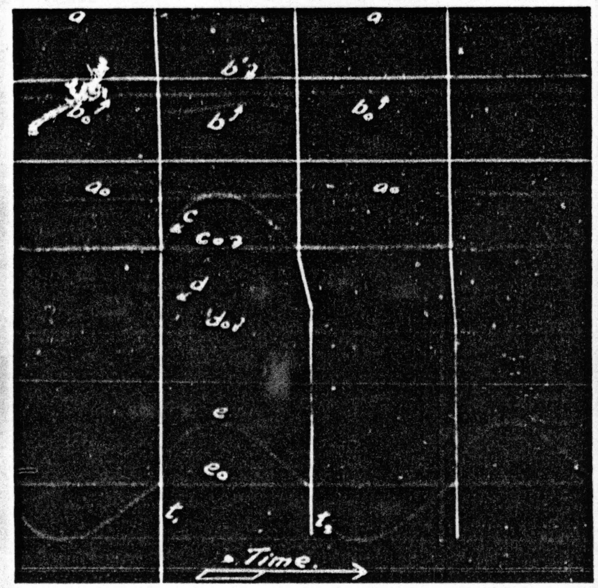

Fig. 9. Oscillograms of the Wave Shapes Obtained with a Direct-current Transformer

a_0—a is the voltage between one thyratron anode and the cathode, b'—b is the corresponding anode current, c_0—c shows the current drawn by one grid, d_0—d is the main transformer secondary voltage and e_0—e is the voltage across the grid transformer.

Not without some difficulty is the imagination restrained from picturing distribution systems of the future using electric valves of different types. It is practically certain that circuits and apparatus of the types described here will be of increasingly greater interest to power system operators.