The Inverter

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In the September, 1924, issue of this magazine, Mr. Prince contributed an article dealing with the tube rectifier and its characteristic wave-forms. In the present contribution the author has taken the rectifier circuit and inverted it, turning in direct current at one end and drawing out alternating current at the other. The new apparatus, consisting of pliotron tubes, transformers, reactances, etc., is known as the "Inverter" and offers a means of converting direct current into alternating without the use of any rotating machines.
—Editor.

The name "inverter" is used to denote the inverse of a rectifier, and covers an assemblage of transformers and thermionic valves of any sort used to convert direct current into single or polyphase alternating current. Such a combination possesses technical interest for the reason that if inverters can be developed in power sizes to have an efficiency and reliability comparable with rotating apparatus they will hold promise for the practicability

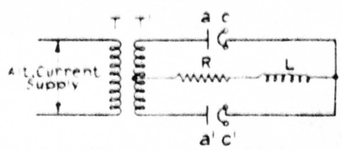


Fig. 1. Rectifier Circuit with Inductance in the Load

of high-voltage direct-current transmission. With such tubes at the receiving end, the power might be supplied by direct-current generators in series or by rectifiers.

The ideal current and voltage relations in an inverter are practically the same as those in a rectifier, provided the inverter is supplying power to rotating apparatus which furnishes a sinusoidal counter e.m.f. These relationships were developed in an earlier article[1] and will be reviewed far enough to show the similarity between inverter and rectifier characteristics.

Fig. 1 is a reproduction of Fig. 3 of the rectifier article, while Fig. 2 is a reproduction of Fig. 4. In Fig. 1 alternating current is supplied to transformer primary T. The secondary T' is connected to the rectifier anodes a, a', so that current flows from whichever is positive. The return circuit of both is by way of inductance L, which holds the current constant, and through load resistance R to the midpoint of winding T'. In Fig. 2, e_p and i_p are voltage and current waves in the transformer primary T, e_a and $e_{a'}$ are potentials of a and a' referred to the midpoint of T', i and i' are the corresponding currents, and e_R and i_R represent drop and current in the load resistance R. The cathodes c and c', which are tied together, have potential wave e_c following whichever anode is positive. The difference between e_c and e_R is the drop across the reactance L.

The ideal single-phase inverter circuit is shown in Fig. 3. It is assumed that the tubes have valve features permitting the interruption of current flowing from anode to cathode, but such features are omitted from the diagram for simplicity, and will be discussed later.

Fig. 3 is similar to Fig. 1 except that a direct-current generator G has been substituted for the load resistance R and a synchronous motor M replaces the alternating-current source.

When the motor rotates with its field excited there is an alternating potential established across T. At the anodes this

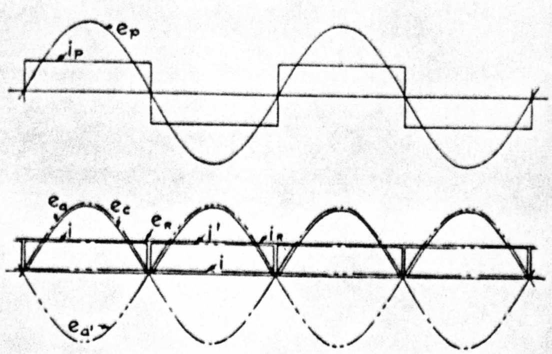


Fig. 2. Primary and Secondary Voltages and Currents of Rectifier Diagrammed in Fig. 1

e_p is the primary voltage, i_p the primary current. e_a and $e_{a'}$ are the voltages of the two halves of the secondary winding. e_c is the cathode potential with respect to the center of the secondary winding. e_R is the load voltage, i_R the load current. i and i' are the secondary currents.

electromotive force alternately opposes and adds to the voltage of generator G. If, during the time the potential at a opposes the generated voltage, the path ac is conducting and current flows, there will be a power input to the motor which will keep it revolving and

[1] See D. C. Prince, "Rectifier Wave Forms," General Electric Review, Sept., 1924, pp. 608-615.

permit it to carry load. On account of the inductance L, the current flow is more or less constant. The voltage induced in L makes up the instantaneous differences between counter and impressed e.m.f.

Fig. 4 can thus be drawn as the equivalent of Fig. 2 for the inverter case, the upper curves representing conditions in the winding T and the lower curves representing conditions in the winding T'.

Referring to Fig. 4, i_p is out of phase with e_p by 180 deg., indicating that the impressed voltage is greater than the counter e.m.f. e_p, so that the current flows against e_p. For the winding T' an attempt is made to show the waves in a manner consistent with the connections; all potentials are measured with respect to the midpoint of the transformer winding. The positive terminal of the generator G is connected to the midpoint of the transformer winding T', the point about which a and a' swing. During the half cycle that $e_{a'}$ opposes e_G the path $a'c'$ is made conducting.

The current $i_{a'}$ then flows. Its magnitude is constant because of inductance L. It flows in opposition to $e_{a'}$ because e_G is enough greater than the average value of $e_{a'}$ to overcome the resistance losses in the wiring. At the instant that $e_{a'}$ and e_a cross, the path ac is made conducting and the path $a'c'$ is made nonconducting. The current i_a then flows, so that the total current i remains steady. The transfer can be made in zero time because the case used is ideal in that the transformer and motor are assumed to have no leakage inductance.

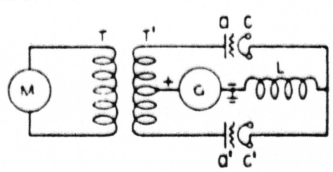


Fig. 3. The Ideal Single-phase Inverter Circuit

The cathodes c and c' alternately follow a and a' in potential, remaining below them by an amount equal to the tube drop. Their path is e_c. The potential difference between e_G and e_c is absorbed by inductance L. Since an inductance will absorb no unidirectional potential, areas included between e_c and e_G above and below e_G must be equal.

For the time being, in order to avoid unnecessary complications in the discussion, we will assume that there is a little devil who makes the paths ac and $a'c'$ conducting at exactly the right times. The requirements set up by transformer and motor inductance must be studied before his duties can be completely outlined. In Fig. 5, Fig. 10 of the previous article[1] is reproduced with only a slight change in the neighborhood of the time t_o.

In order to secure the highest set efficiency the tube losses should be held to a minimum. If current transfer from one tube to the other

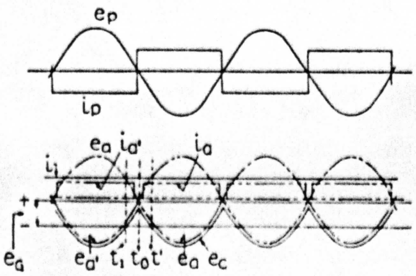


Fig. 4. Primary and Secondary Voltages and Currents of Inverter Diagrammed in Fig. 3

e_p is the primary voltage, i_p the primary current. e_a and e_a' are the voltages of two halves of the secondary winding. e_c is the cathode potential with respect to the center of the secondary winding. e_G is the impressed voltage, i_G the load current. i and i' are secondary currents.

is forced by increasing the resistance in one, and decreasing it in the other, there will be resistance losses in the tubes during transfer. If both paths are made wholly conducting, and the current is caused to transfer naturally, all transfer loss may be avoided. During the time that both tubes are conducting, current will tend to flow in the circuit $T'acc'a'$, and by induction in circuit TM in response to the voltage generated by motor M. The voltage from G is neutralized entirely by the drop in inductance L, since the motor can furnish no counter e.m.f. at this point while both paths are conducting. This is so because of the symmetry of the winding T'. The induced voltages in both halves are equal and are entirely absorbed by equal impedance drops while both tubes are conducting.

The current which would tend to flow is of the usual transient form shown by the dotted curve i, Fig. 5. In drawing this trace it is assumed that resistance is small compared with reactance, so that the current is nearly 90 deg. out of phase with the voltage producing it. The axis u approaches zero exponentially.

In the case of the rectifier the change in relative polarity of a and a' was in the proper direction to transfer the currents naturally beginning at time t_o, corresponding to the instant of zero induced voltage in the transformer, and ending at time t', but in that case it was proper for the current to be in phase with the alternating voltage. Now, however, it is desired to have the current flow in opposition to the alternating voltage. It is

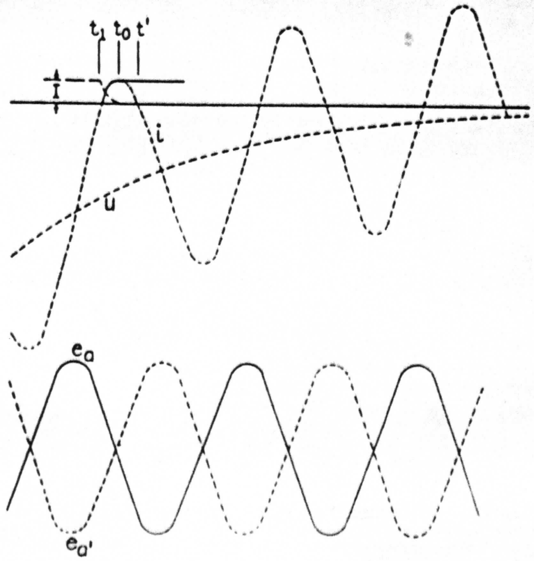


Fig. 5. Graphical Representation of Conditions Arising from the Supposition That the Transformer Shown in Fig. 3 Has Inductance

apparent from Fig. 5 that prior to time t_o current was shifting in the opposite direction. There should be a time t_1 at which the two paths might be made conducting with the resulting transfer as desired. At t_o the forces causing current change become hostile, so at this point, the path from which current has been transferred should be made nonconducting.

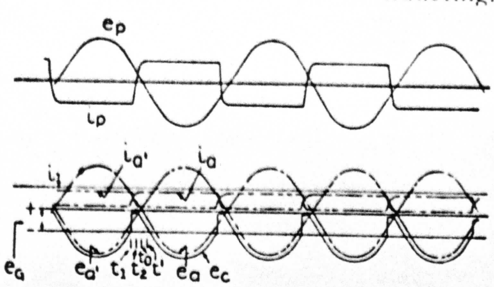


Fig. 6. Current and Voltage Waves Showing Effect of 26 deg. Period of Short Circuit During Which Currents Are Transferred and no Voltage is Produced by the Inverter

To put this proposition in another way: referring to Fig. 4, the two cathodes are following e_c and are approaching e_a at time t_1. Potential $e_{a'}$ is only sufficiently positive with respect to e_c to make the current flow, but e_a is very much more positive. At t_1, then, the path ac is made conducting and the potential difference between e_a and e_c is available to make current flow through ac in preference to $a'c'$. When t_o is reached, the current has all chosen the path ac. The path $a'c'$ is then made nonconducting so that the current can not return, although the forces are in the reverse direction.

As a matter of calculation, suppose that the voltage induced in motor M is sufficient to circulate a current whose peak is ten times the direct-current I, Fig. 5. Then, neglecting resistance, the period t_1t_o will occupy 26 deg. of electrical arc ($1-\cos$ 26 deg.$=0.1$), so that a current whose amplitude is ten times normal will reach normal in 26 deg. The little devil is then instructed to open the gate at 26 deg. before zero hour and shut it at zero sharp.

It is important that he shut the gate at zero sharp, or even a little before, for safety. He may anticipate the 26 deg. however. If the transfer is commenced before time t_1 the current will all be transferred from path $a'c'$ to path ac before time t_o. At the termination of transfer there will still be a potential tending to make current flow in ac, in preference to $a'c'$, but current cannot reverse in $a'c'$ because the valves possess conductivity

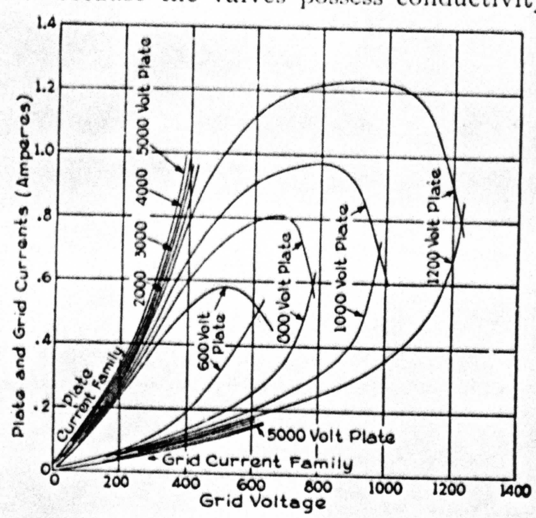


Fig. 7. Pliotron Characteristic Curves

in only one direction. The current in $a'c'$ therefore remains at zero until t_o when the gate is closed.

If the path $a'c'$ were not rendered nonconducting at t_o, current would begin to flow again in this path. A three-electrode vacuum valve has the property of closing very positively, so that if it closes on a circuit carrying current, violent oscillations are almost invariably set up. It is important, therefore, that the current be brought to zero a short time before t_o and the valve be closed between that time and t_o.

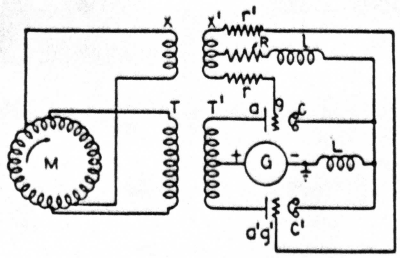


Fig. 8. Diagram of Inverter Showing Method of Deriving Grid Excitation

During the time that current transfer is taking place, the counter e.m.f. is the average of e.m.f.'s induced at a and a'. The difference is all consumed in the inductance of the windings. In the single-phase case this average is zero, but in polyphase cases it is not zero. If the time of transfer is ended before t_o, the counter e.m.f. becomes the potential e_a which is not in opposition to e_G

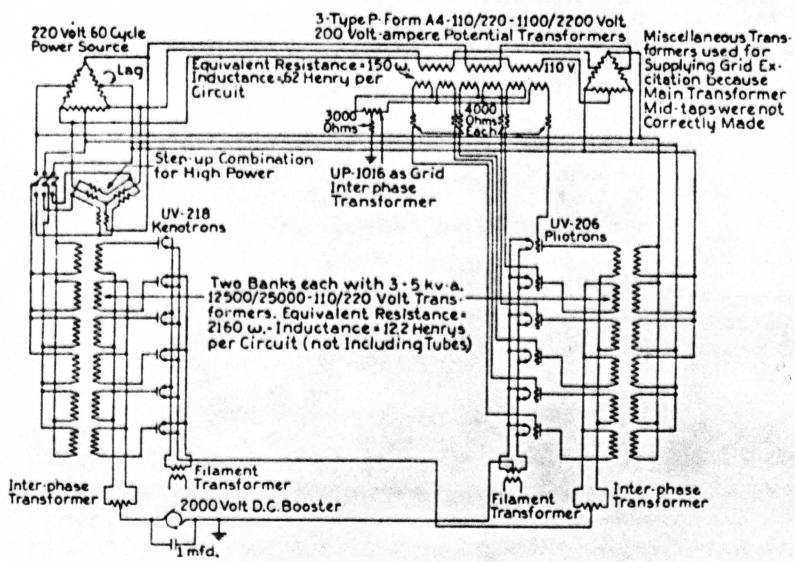


Fig. 10. Circuit Diagram of 15,000-volt Rectifier and Inverter

until after t_o. There is, therefore, a time during which the inductance L must absorb more than the impressed direct potential. Fig. 6 corresponds to Fig. 4, but includes the effect of leakage reactance.

At time t_1 (Fig. 6), path ac becomes conducting and current begins to shift from $a'c'$ to ac. At t_2 the transfer is complete. Between t_1 and t_2, e_c was below the average of e_a and $e_{a'}$ by just enough to make current flow. By t_2 all the current is flowing in path ac, and e_c accordingly jumps to a distance below e_a just sufficient to maintain the current. Path $a'c'$ is made nonconducting at some time between t_2 and t_o, but this does not produce

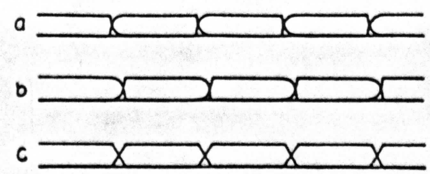


Fig. 9. Comparison of Current Waves
(*a*) Inverter current wave form
(*b*) Rectifier current wave form
(*c*) Grig current wave form

any changes in the waves because no current is flowing in $a'c'$, and no current change is produced.

The foregoing discussion is general in that the type of valve device is unimportant. No matter what the means of cut-off, the conditions to be fulfilled are the same. The two paths involved in the transfer are both made conducting during a period when the voltage relations are right to produce the transfer. After the transfer is complete, the path carrying no current is rendered nonconducting. The only other requirement is that the paths possess unidirectional conductivity. Without this property the valve closing must be exactly timed and this is not possible in circuits where all the factors are fluctuating to some extent.

The grid of a three-electrode valve, or pliotron, may be controlled from the alternating-current circuit in such a way as to do the work of the little devil nearly as well as he can do it himself. Fig. 7 is a set of characteristic curves of a General Electric one-kilowatt pliotron. It is apparent that a rough proportionality exists between plate current and grid current, so that if we make certain that the grid of a tube is drawing current, then that tube is in a conducting state. As already pointed out, there is a close similarity between rectifier and inverter characteristics. The required grid potential changes resemble closely the normal potential changes of the anodes of a rectifier. We will then combine Fig. 1 and Fig. 3 into Fig. 8.

All the elements of Fig. 1 and 3 are here included, and, in addition, resistances r and r'. The grid transformer primary x is connected to points of the motor winding M so as to have a phase advance of a little more than half the time between t_1 and t_0. The purpose of resistances r and r' is best explained by reference to Fig. 9. Part *a* of this diagram gives the form which the main anode current waves will naturally take. On account of the proportionality between anode and grid currents, the grid current wave should approach this form as nearly as possible.

But an actual rectifier has a current waveform such as shown in Fig. 9-b. The transfer begins very gradually just when the maximum rate of change is required in the anode circuit. If the resistances r and r' are inserted, the two grids will begin to divide the current as soon as the potential difference between grids becomes equal to the $i_g r$ drop in the particular resistance carrying the grid current. The grids will continue to divide the current until the grid potential difference has reversed and reached the value equal to the $i_{g'} r'$ drop. If the resistances r, r' are large compared with the reactance in the grid transformer circuit, the transfer current will be similar in shape to the voltage during the transfer period, i.e., nearly linear for a sine wave near zero. The linear transfer as shown in Fig. 9-c is still not the same shape as the anode transfer in Fig. 9-a, but it may be made to have a sufficient initial slope for the beginning of transfer and an excess slope thereafter without causing excessive grid loss.

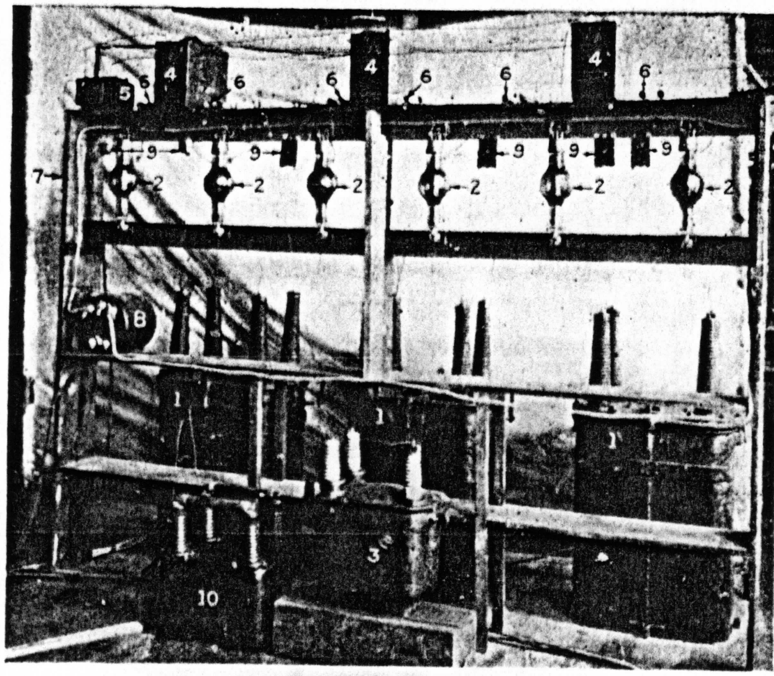


Fig. 11. Set Built for Laboratory Use

From Fig. 6 it appears that, due to the inductance of motor and transformer, the current and voltage in the alternating-current circuit are not exactly 180 deg. out of phase.

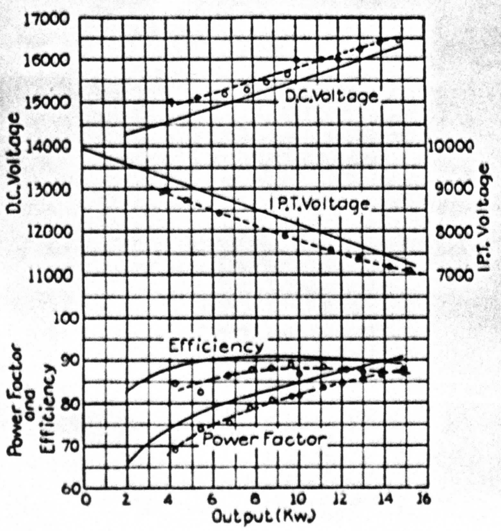


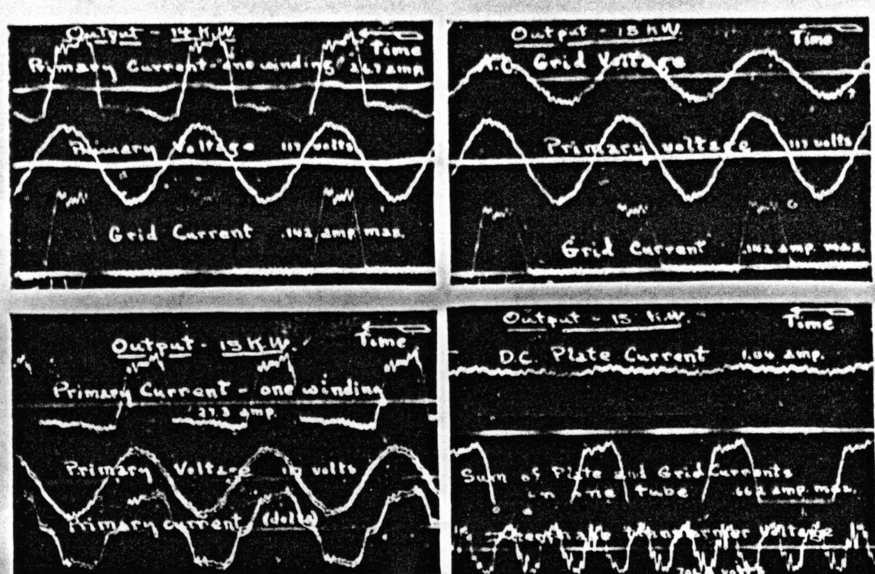
Fig. 12. Characteristics of Set Shown in Fig. 11

This means that a wattless component must be supplied by the motor; that is, it must either be a synchronous motor, or must be associated with condensers to supply the wattless component.

It may be objected that no means are given for starting the apparatus or for governing the speed after it is started. The criticism is well founded for the arrangement shown. However, arrangements of condensers and inductances will accomplish the same purpose, and at the same time be self-starting. Once oscillations are started power is available to start up motors and other rotating apparatus.

The frequency determining element in the arrangements shown is the synchronous motor M. Once this machine is rotating the direct-current drawn is determined by its counter e.m.f. If it slows down, the counter e.m.f. is reduced and more current is drawn until the speed is restored.

Fig. 10 is a connection diagram of a set figured along the lines suggested above. Fig. 11 is a photograph of the set built for laboratory use. Fig. 12 shows the characteristics of this set as determined by calculation and as observed experimentally. The performance on an absolute basis is not remarkable; however, the close correspondence between calculations and tests indicates that when tubes are developed to a stage comparable with other power apparatus, the practicability of high voltage direct-current transmission, with vacuum tubes in the converting apparatus, will probably not be far distant.



Typical Oscillograms of Inverter Performances