GASEOUS DISCHARGE
RECTIFIER & CONTROL-RECTIFIER
TUBES

ENGINEERING MANUAL
AND
CATALOG

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FOREWORD

THIS Engineering Manual and Catalog relates to hot-cathode gas-filled tubes developed by ELECTRONS, Inc. after systematic research with gaseous discharges. They are manufactured by specialists in rectifiers and control rectifiers exclusively, to meet the demand for power tubes of extreme reliability.

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INTRODUCTION

HISTORICAL

INERT vapor filled rectifier tubes were proposed as early as 1906 and grid control rectifier tubes in 1912. Despite these early experiments, the complex difficulties encountered in meeting reliability requirements hindered the commercial development of these classes of tubes.

A number of factors contributed to this. Though not appreciated for some time, the degree of degassing during evacuation suitable for high-vacuum tubes proved utterly inadequate for long-lived gaseous tubes. The ordinary oxide cathode of high-vacuum tubes flew off in a shower of sparks under the severe ion bombardment. Trouble was encountered in maintaining characteristics under no load operation. Coordination of tube design and protective equipment was required.

Tubes developed by Electrons, Inc. as early as 1928 having specially devised tough cathode coatings successfully withstood the heavy ion bombardment encountered in industrial applications of gas-filled tubes. This, and improvements in manufacture, did much to lengthen the life of gaseous discharge rectifiers.

Operating records of EL rectifiers made in 1929 and 1930 showed many tubes having tens of thousands of hours of life, though the average life was decreased by some tubes of short life. Since then the percentage of short lived tubes has steadily decreased and operating conditions have been corrected to insure a reasonable certainty of long minimum life.

Electrons, Inc. is very proud of the outstanding performance of its products in the services of the armed forces during World War II. Approval by the Services was attested by two awards of the Army-Navy "E" and by many Electrons, Inc. designs that appeared on the Joint Army-Navy tube Preferred List.

GENERAL CHARACTERISTICS

An EL rectifier consists of an evacuated envelope containing a filling of extremely pure Xenon gas at reduced pressure, a heated electron-emissive cathode, and an anode. When the anode is positive, electrons are attracted to it from the cathode and constitute a current flow. In their passage they ionize the gas. The ions neutralize the space charge of the electrons, and thereby eliminate nearly all of the internal resistance of the tube, leaving only a drop of five to twelve volts depending upon the design. The anode is non-emissive, hence no current flows when it is negative.

An EL Control Rectifier differs from the above in that a non-emissive grid is inserted between the anode and cathode. Small variations of the grid potential permit or prevent the start of the main current in the anode circuit when the anode is positive. Once the main current is allowed to start, the grid has no further control until the anode voltage is reduced to zero, or made negative for a small fraction of a second as with a-c. supply voltage. In this way, minute grid energy can control large amounts of power.

Xenon gas, first used by Electrons, Inc., has practically the same space charge neutralizing power as mercury, yet is unaffected by surrounding temperatures. Xenon-filled tubes require no temperature control and have no temperature effects on control characteristics, rating, or life, thereby enhancing reliability.

APPLICATIONS

The possible uses of rectifiers are self-evident to those who require direct current. A gaseous tube rectifier is indicated where the output voltage is several times larger than the tube voltage drop. Below this range contact rectifiers are usually preferred.

Many rectifier applications have more than offset tube costs by the saving in power from increased efficiency. Often substantial savings result from the fact that tube devices do not require regular maintenance by mechanics or electricians, as anyone can replace a tube. Many installations are made to avoid noise, or to eliminate the fire risk of unattended rotating machines.

To describe the field of usefulness of grid-control rectifiers is difficult. However, it may help to indicate the possible applications by listing the principal functions accomplished with grid control tubes in some of the various existing installations.

1. Control of a motor for either
    a. Servomechanism response, whereby some motor-driven device is made to follow quickly and accurately the motion of some delicate or remote instrument or circuit condition.
    b. Precise, or wide-range speed control.
2. Control of a power circuit from a very feeble or low-energy control circuit or controlling device, particularly where either high-speed response or delicate variation of output power is required.
3. High-speed or synchronous switching circuits, such as welders, x-ray contactors, saw-tooth oscillators and high-speed counting or inspecting equipment.
4. High power vibrating motors, or pulsed magnets.
5. Inverters for changing frequency or for changing d.c. to a.c.

In a large percentage of applications it is essential that the chance of shutdown be remote. A study of installations involving thousands of tubes after years of service has shown many cases where the loss of availability of the installation, due to tube failure, was less than from failure of common mechanical or electrical equipment.

Electrons, Inc. manufactures tubes only. Complete units in which the tubes are applied require properly designed transformers, sockets, protective devices and other equipment. Tube life and the performance of the unit are affected by the design of all components of the unit. Application engineers of Electrons, Incorporated are available to offer assistance to the equipment designer.

PATENTS

EL Rectifiers and Grid Control Rectifiers are manufactured and licensed under one or more of the following issued United States patents:

Re. 18,798
1,723,888
1,784,877
1,790,152
1,790,153
1,814,499
1,817,636
1,866,729
1,873,683
1,874,753
1,880,092
1,883,174
1,903,144
1,903,145
1,905,692
1,910,557
1,924,058
1,925,701
1,928,202
1,928,203
1,929,043
1,929,661
1,931,254
1,934,830
1,941,076
1,946,603
1,953,906
1,985,855
1,986,627
1,987,998
1,989,132
1,993,187
1,995,017
1,995,018
2,003,609
2,011,922
2,012,339
2,021,482
2,023,453
2,023,707
2,040,768
2,044,350
2,054,030
2,065,997
2,068,539
2,070,816
2,081,864
2,085,696
2,111,506
2,173,473
2,175,019
2,181,366
2,185,832
2,203,639
2,206,912
2,223,031
2,282,998
2,320,224
2,383,263
2,443,100
2,456,540
2,459,997
2,489,858
2,489,937
2,489,938
2,493,575
2,513,255
2,538,053
2,538,054
2,565,004
2,567,369
2,605,432

All of Electrons, Inc. gaseous tubes carry with them automatically a license to use such tubes under all patents owned by the company.

WARRANTY

Tubes manufactured by Electrons, Inc. are warranted to have a useful life in excess of 3,000 hours if used under proper conditions without exceeding the published ratings and engineering catalog recommendations. This warranty is limited to replacement of tubes which fail as outlined below. Those tubes which fail in service in less than 3,000 hours may be returned to us for examination with a statement as to conditions of operation and failure. If our tests indicate that the tube was defective, credit will be allowed for the unattained portion of 3,000 hours. Defective tubes, under this warranty, must be returned within 18 months of their original purchase.

AVAILABILITY

EL Rectifiers and Control Rectifiers are stocked by distributors in many cities of the United States and Canada for the convenience of users requiring replacement tubes. Sales to manufacturers of equipment incorporating tubes are handled directly from the factory.

DESIGN OF RECTIFIER UNIT

CIRCUITS

A TUBE RECTIFIER requires alternating current supplied to each anode at such a voltage that the rectifier will deliver the desired d-c. output voltage, and a separate supply of current to heat the cathode. A transformer is usually used having a winding for each anode and for the cathode heating voltages.

The tube required, the d-c. voltage wave shape, and the transformer requirements depend on the circuit chosen. The first step in the design of a rectifier unit is, therefore, the choice of the most suitable circuit. Table I on page 13 lists several common circuits, and gives the output voltage wave shape, current and voltage relationships of each.

In any circuit the tube allows current to flow as soon as its instantaneous anode potential, relative to the cathode, exceeds the tube starting voltage. Therefore, at any instant during the conduction period, the output voltage is equal to the instantaneous a-c. voltage minus resistance, reactance and the constant tube drop. This current flow continues until the tube is relieved by another tube or the instantaneous output voltage less voltage generated by the load, drops to zero. The output voltage read on a meter will be the summation over a complete cycle of all the instantaneous output voltages. The instantaneous current equals the instantaneous output voltage less any back e.m.f. or voltage induced in the load, divided by the load resistance. Since meter readings are based on the summation over a whole cycle rather than instantaneous values, it is necessary to know the average (d-c. meter) value and r.m.s. or heating (a-c. meter) value of these currents, to design the circuit.

Ordinarily, parallel operation of gaseous discharge rectifiers is difficult because the inductances necessary to distribute the load become too large for good regulation. When current output must be increased it is customary to go to polyphase circuits. Polyphase rectifiers have a decided advantage in that they can be designed to continue operating even if a single tube fails.

EL Rectifiers may be connected in series where higher output voltages are required, as shown in Figs. 3 and 6 of Table I on page 13.

Circuit 1 is used only where a large ripple in the output is not objectionable. It requires a butt joint in the magnetic circuit of the transformer to prevent saturation of the transformer core due to the unbalanced d-c. component of current in the anode winding. With circuit 4, a 3-legged, 3-phase transformer core minimizes the d-c. magnetization. Delta primaries are desirable for polyphase circuits because the load carried by a single secondary coil is discontinuous, and the mid-point voltage of a star-connected primary does not remain fixed under these conditions. With bridge type circuits it is immaterial whether star or delta connections are used. Where variable d-c. output voltage is required a variable transformer may be used to supply the anode voltages. A saturable reactor is sometimes used in series with the anode transformer supply to regulate the output if this is desired, although the use of grid-control tubes is usually preferable, especially where fast response is desired.

TUBE RATINGS

The selection of the circuit establishes the tube ratings that are required for a given d-c. load. Given the desired output voltage V and current A, the required tube peak inverse voltage and average anode current may be computed using the factors given in Table I. A summary of ratings of available tubes is given on the price list.

A rectifier tube has two essential ratings.[8]

(1) ANODE CURRENT

The greatest continuous current the tube can pass when its anode is positive without danger of overheating or reducing its life is called the average anode current. Since tube heating is proportional to the average current, tubes are rated in d-c. rather than a-c. amperes. EL Rectifiers will withstand overloads with only a moderate shortening of life, hence overload ratings are given also in d-c. amperes. Repeated high instantaneous currents for short periods may, under certain conditions, shorten life even if the average current rating is not exceeded. Tubes, therefore, have maximum instantaneous current ratings for normal operation called the maximum oscillograph peak current.

Anode thermal capacity is a limiting consideration within the oscillograph peak current rating. For short times, the safe permissible overload may be computed by dividing the product of the averaging time and the continuous average anode current rating, by the proposed conduction time.

Also provided the oscillograph peak current rating is not exceeded, the following duty may be repeated every thirty seconds. This is computed by subtracting the average current rating from the overload rating, then multiplying the difference by either the time in seconds that applies to the overload rating or the averaging time, whichever is less, to obtain an overload ampere-second rating. For any given time, less than the stated averaging time, the average current rating may be exceeded by an amount equal to $\frac{\text{overload ampere-second rating}}{\text{seconds overload is applied}}$.

(2) PEAK INVERSE VOLTAGE

The greatest instantaneous negative voltage that may be applied to the anode without danger of reverse conduction, or failure is called the maximum-rated peak inverse voltage.

(3) CHARACTERISTICS

In addition to these ratings a rectifier tube has characteristics whose value and expected range of variation are important. They are:

a. Cathode heating voltage, current and time.

b. Arc drop, or positive potential of the anode relative to cathode, or filament center tap, during conduction of current. The value given in the tube data sheets is the average for steady operation at rated resistive load. On any tube it may increase or decrease with load or during life. There are transient variations on change of load, filament voltage or anode current wave shape. However, the total change from all sources on any tube during the entire life, averaged over a period equal to the heating time, should not exceed the range given. Variations due to current change on any one tube seldom exceed one-third the range.

c. Anode starting voltage is the instantaneous positive potential of the anode relative to cathode necessary to initiate the conduction current.

d. Commutation characteristics, or frequency limitations. (See page 23.)

e. Short circuit current limits and maximum duration of short circuit current.

ANODE TRANSFORMERS

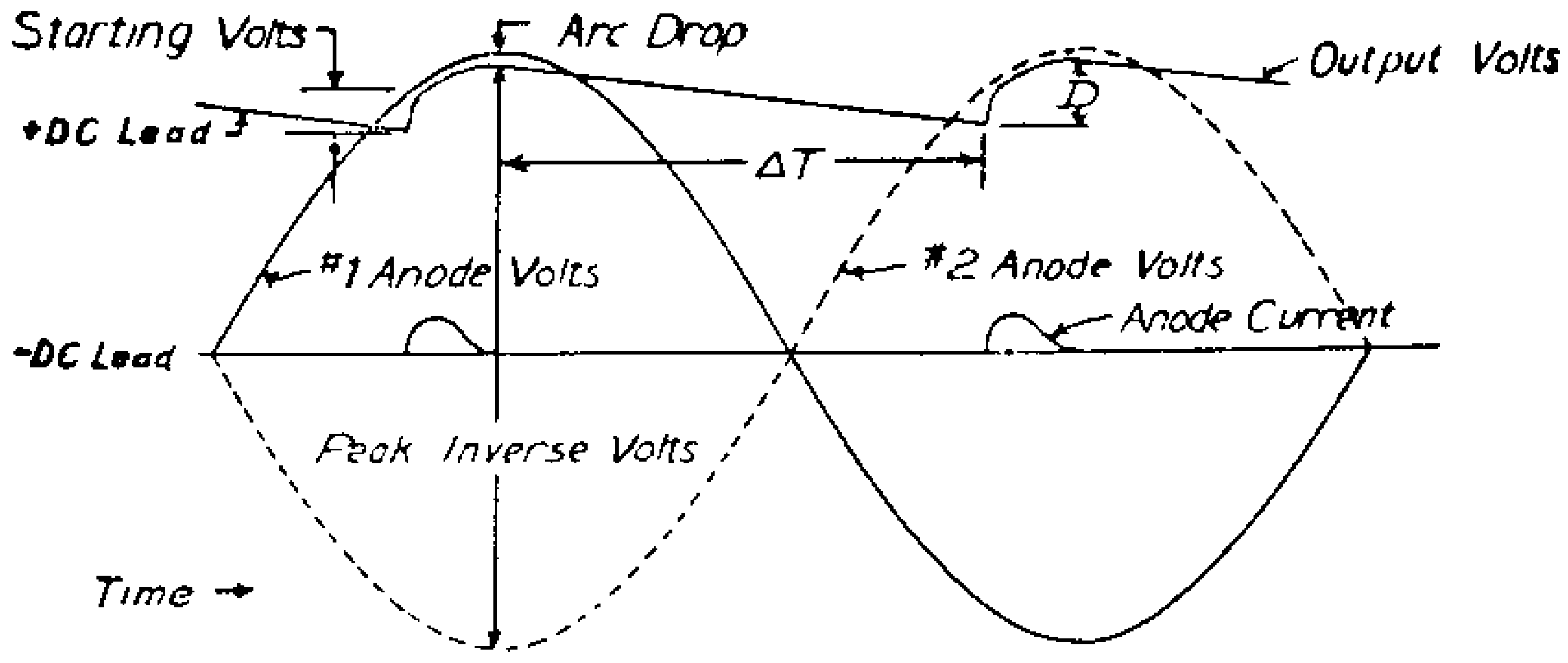
(1) RESISTIVE AND INDUCTIVE LOADS OR FILTERS

Data for the transformer secondary winding necessary to supply the d-c. load for the various circuits is given in Table I on page 13. The usual design procedure is to assume ideal rectifiers and transformers, then use the factors in Table I to calculate the a-c. anode voltage necessary to give a d-c. voltage equal to the desired amount plus the average tube arc drop. Series circuits (Figs. 3 and 6, Table I) use twice this drop.

The differences between a real and ideal rectifier are taken into account if an accurate design is required by allowing for regulation under load as described later, and in low voltage rectifiers, for the effect of the tube starting voltage*. Due to the wave shape of the current in the anode circuit, d-c. and a-c. ammeters give quite different readings. Copper losses and transformer heating depend on the a-c. value of the current flowing in the various windings. Hence the factors in Table I must be used to compute the a-c. current. For many rectifier transformers the kva. rating of the secondary must be higher than that of the primary winding. Both are higher than the d-c. meter value of the output.

(2) CAPACITIVE LOADS OR FILTERS

A capacitive load, or a large capacitor in parallel with any other type of load, may be used with the circuits shown above, but the mode of operation is changed to that of a crest rectifier and the circuit constants given in Table I no longer apply. The rectifier output current is discontinuous, load being carried mainly by the capacitor which is recharged periodically by the a-c. anode-voltage wave. This condition of operation for Circuit 2 is shown in the following sketch of the instantaneous voltages relative to the anode-transformer center tap.



Each anode, during its conductive period, charges the capacitor to a voltage equal to 1.41E, minus arc drop. The tube then stops conducting and the capacitor carries the load until the next conduction period. During this time, the capacitor is discharged an amount given in volts by the following formula:

$$D = \frac{A(\Delta t)10^6}{C}$$

where A = d-c. amperes output,†
C = capacitance in microfarads,
Δt = discharge time in seconds,
f = supply frequency,
p = rectifier phases (See Table I).
D = decrease in capacitor voltage.

As a first approximation, Δt may be taken as 1/fp, on the assumption that the time required to charge the capacitor is a negligible part of the total. Later, the exact Δt may be determined by deducting from the approximate value the charging time, measured from the point in the cycle where the tube fires, to the top of the anode-voltage wave. An anode starts conducting as soon as the instantaneous anode voltage exceeds the capacitor voltage, plus tube starting voltage. The d-c. output voltage of the rectifier can be estimated from the peak capacitor voltage minus D/2.

The peak capacitor charging current is much higher than the load current. It is usually measured with an oscilloscope rather than attempting to calculate its value. A-c. transformer currents are best found experimentally. Page 275 of reference 5 listed in the bibliography on page 31 treats this circuit mathematically.

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* The starting voltage causes a reduction of output voltage. The resulting output voltage of resistive or inductive loads for circuits 4 and 5 is

$$V_1 = V_o\left(\sqrt{1 - \frac{\overline{SV}^2}{2B^2}}\right)$$

where V_1 = corrected d-c. voltage,
V_0 = d-c. voltage assuming zero starting voltage of tubes,
B = a-c. rms voltage between successively firing anodes,
SV = Tube starting voltage.

For circuit 2 on inductive loads the above formula is used but with resistive loads the resulting output voltage is

$$V_1 = V_o\left(\frac{1 + \sqrt{1 - \frac{\overline{SV}^2}{2B^2}}}{2}\right)$$

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† Rigorously, the instantaneous value of A should be averaged over the discharge period. Where the discharge is less than V/3 it is permissible to use A without introducing serious error.

Whether a load appears as a capacitance or resistance depends on the rate at which the capacitor discharges. If D exceeds V/3 the circuit approaches a resistance load in operating characteristics.

TUBE PROTECTION

Gaseous tubes are not seriously damaged by short circuit if the current is interrupted promptly, but they overheat rapidly because of their high efficiency, and because of the light material used to permit thorough degassing. This fact has aggravated the protection problem by requiring that fault currents be cleared before parts melt or glass cracks at the lead-in wire. The conditions to be protected against are as follows:

1. Application of d-c. load before the cathodes are fully heated.
2. Prolonged overload current that might overheat the transformer or tube.
3. Short circuit current. This may be a d-c. short circuit, or, what is equivalent, a short circuit from anode to anode.
4. Surge voltages in either the a-c. or d-c. side.

EL Rectifiers are carefully designed to withstand the short circuit conditions listed in the individual tube data sheets. In designing the protective system it must be remembered that both fuses and breakers operate in response to the r.m.s. value of current flowing. During short circuit of a rectifier each anode secondary voltage is short circuited through one or more tubes. Secondary voltages are available to force short circuit current to flow through the secondary reactances with only negligible voltages absorbed by the tube. Each anode carries a pulse of current nearly 360 degrees long, and all anodes in the circuit conduct simultaneously. This reduces the form factors to approximately 1.1 so that the r.m.s. currents do not increase as much as the d-c. currents which heat the tube. As a result, the tripping current of the circuit breaker does not increase over full load current as much as might be supposed, four times being common with usual power supply source impedance. To operate the ordinary fuse or breaker in its rated short time usually requires a tripping current ten times rated current, with the result that these devices do not operate promptly or reliably in rectifier applications. On the smaller tubes Littelfuse Inc. fuses or standard fuses (not lag fuses) operate satisfactorily and give adequate protection on many circuits. As the power goes up, a point is reached where standard fuses and many circuit breakers are unreliable. Fortunately there are now several breakers on the market which work well with four times normal current.

It seems to make little difference whether interruption is by opening the anode circuits or by opening the a-c. primary circuit. If there is a source of energy in the load such as a battery or running motors, the d-c. circuit must also be opened. On some occasions primary switching is better as the primary is a-c. current, whereas the anode circuit is practically carrying d-c. and has available the full peak inverse voltage. If primary breakers are used, the trip coils must have enough time delay to allow transformer magnetizing inrush current to flow without tripping the breaker.

FILAMENT CIRCUIT

A winding on the anode transformer or a separate transformer may be used to supply the filament heating current. Overheating the filament shortens tube life by evaporating the cathode, while insufficient heating damages the emissive surface by excessive ion bombardment, hence consideration must be given to the accuracy of the filament voltage.

A variation of plus or minus 5% with short periods of plus or minus 10% has little effect on tube life. Continuous operation at plus or minus 10% will be damaging unless certain reduced tube ratings are observed. **It is recommended that rectifier units give at least the correct filament voltage, plus or minus 0.05V on a 2.5-volt filament at the socket, with the tube in place and correct supply voltage applied.** This allows reasonable supply voltage variations without exceeding the tolerable range.

Filament windings of full-wave tubes should be center-tapped for the d-c. positive lead to eliminate line frequency components of voltage from the output, and to properly distribute the load over the filament. Full-wave tubes used in polyphase circuits should have polyphase filament-heating circuits, with the correct phase applied to each filament. On most half-wave tubes, a center-tapped filament transformer winding is recommended for the positive lead to the load. The recommended filament phasing is shown on the individual data sheets.

With all tubes it is desirable, and with some it is essential, to heat the cathode to operating temperature before load current is passed through the tube. Even where this is not essential, many installations have shown that a time-delay relay in the load circuit saves enough tube life to repay its cost many times. The anode and filament voltages may be switched on together if the d-c. load is disconnected.

EFFICIENCY

The efficiency of a rectifier may be computed from the output, and the sum of the following losses:

1. Tube cathode heating power. (This is the filament voltage x filament current x number of tubes.)
2. Tube arc losses. (Arc drop x average current per tube x number of tubes.)
3. Transformer copper and core losses. (Sum of the products of transformer resistances x the square of the r.m.s. currents flowing through each resistance + separately measured core losses.)
4. Harmonic power in the output if this is not useful. (Applies only to unfiltered resistive loads.)

REGULATION

Resistive and Inductive Loads

The regulation at loads from about ten milliamperes to overload rating depends upon the circuit and transformer characteristics, rather than upon the tube. The drop in voltage when load is applied to full-wave and polyphase rectifiers, may be considered as three separate voltage drops, which, added arithmetically, give the total reduction; these are, a transformer resistance drop, a commutation drop due mainly to leakage flux between transformer secondary windings, and a reactance drop due to leakage flux in the primary windings.

The resistance drop is equal to*

$$Dr = A(N^2R_1 + R_2)$$

where Dr = volts drop in d-c. output due to resistance,
R_1 = resistance of winding marked I_1,
R_2 = resistance of winding marked E,
A = total d-c. current,
$$N = \frac{\text{Turns in winding E}}{\text{Turns in winding marked } I_1}$$

Where a filter choke is used, its resistance Rc causes an additional drop equal to ARc.

Transformer leakage flux between successive secondary windings, tends to prolong the time required for the current to transfer from one anode to the next. During this short period of transfer, both anodes conduct, and the instantaneous output voltage is the average of the two anode voltages rather than the highest. This period of commutation of the current from anode to anode lowers the d-c. output voltage by

$$Dc = KAX_1$$

where Dc = drop in d-c. output voltage due to commutation,
X_1 = effective reactance at supply frequency measured between two successive anode connections with the primary shorted,
K = regulation constant given in Table I,
A = total d-c. current.

This formula does not apply at loads so great that more than two anodes conduct simultaneously. If the calculated drop is in excess of 15%, it would be best to consult one of the textbooks listed in the bibliography, to see

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* For circuit 6 two windings are in series and R_1 and R_2 are doubled.

whether the range of this equation has been exceeded.

The reactance drop appears on resistive loads only and is usually insignificant. It may be estimated with sufficient accuracy for practical purposes by †

$$D_L = V\left[1 - \sqrt{1 - \left(\frac{AX_2}{E}\right)^2}\right]$$

where D_L = volts drop in d-c. output due to reactance,
X_2 = transformer reactance measured across winding E of the secondary with the primary shorted,
V = no-load d-c. output voltage,
A = total d-c. current,
E = a-c. plate volts.

Capacitive Loads

At very light loads, a crest rectifier fires only at odd intervals, and the capacitor carries the load for many cycles until it is discharged enough to allow another pulse of anode current to pass. The recharge occurs whenever the capacitor voltage is less than 1.41E, minus the tube starting voltage. As load is applied, the number of discharges increases until finally each anode is firing each cycle. Over this range there is no change in average d-c. output voltage, although the voltage fluctuates over a range equal to starting voltage less arc drop. Additional load increases the discharge during the cycle without affecting the peak voltage to which the condenser is recharged. Usually sufficiently accurate results can be obtained by assuming the drop in output voltage is half the difference between the condenser discharge and the starting voltage.

In the rectifier circuit with capacitor load the tube peak current may be limited to oscillograph peak current ratings by the addition of sufficient leakage inductance in the anode transformers or supply, plus additional inductance if required. This inductance may be enlarged to increase the tube conduction period as compared with the usual crest rectifier. This results in two important advantages. First, the tube peak current is limited without power loss, and second, improved regulation is obtained with a given filter capacitor, or, at fixed regulation a smaller capacitor may be used with some increase in ripple.

FILTERS

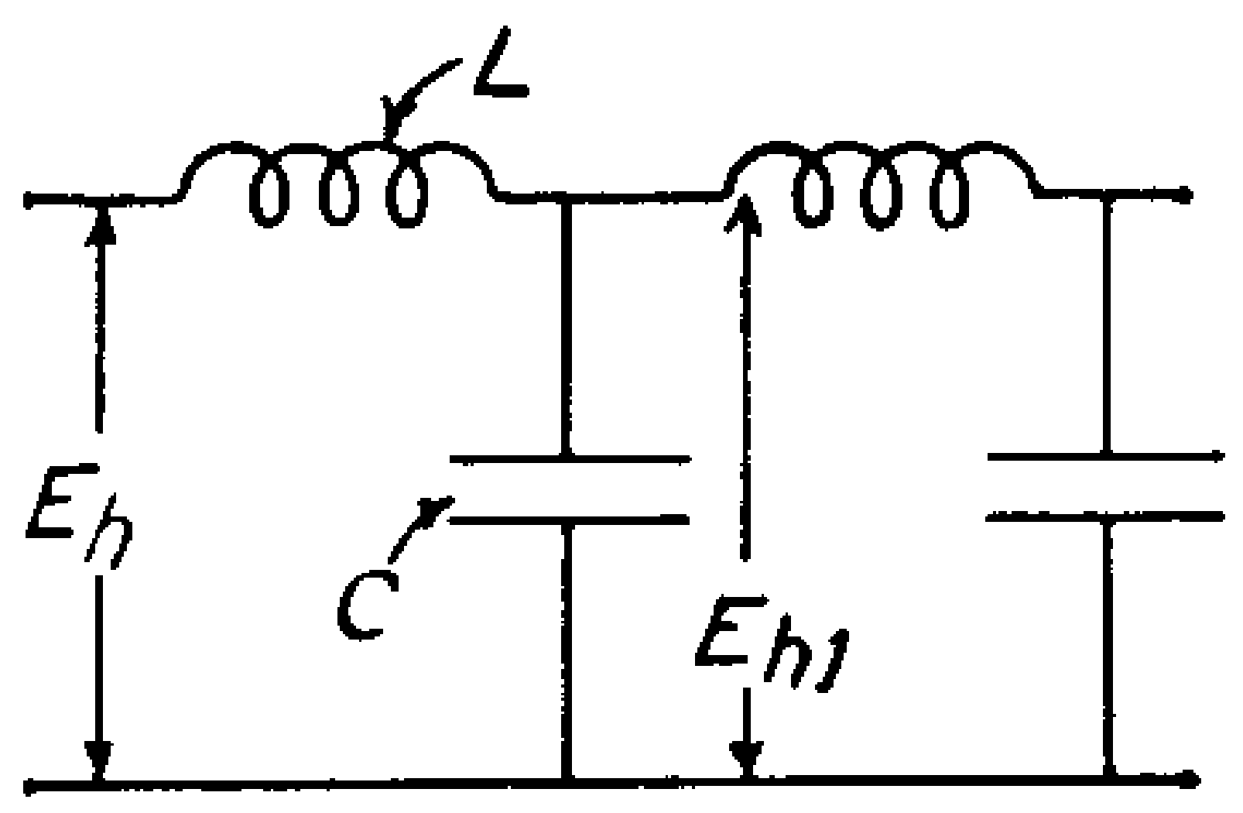
The output voltage of a rectifier may be filtered by inductance, capacitance, or both. Where a capacitor is used immediately at the output of a tube, it must be at least large enough to make the load appear capacitive to the tube to have much effect.

Where a single inductor is to be used next to the tube, its size may be estimated from the following formula:

$$L = \frac{E_h}{2\pi f_h I_h}$$

where L = inductance in henries,
E_h = a-c. value of the major ripple voltage of the rectifier output (Table I),
f_h = frequency of the major ripple output voltage (Table I),
I_h = permissible a-c. current in the output.

In a composite sectional filter the ripple voltage divides across the first section in the ratio of the reactance, at the major ripple frequency, of the parallel capacity to the reactance of both inductor and capacitor in series.



$$E_{h1} = \frac{E_h}{(2\pi f_h)^2 LC - 1}$$

The voltage appearing across the capacitor of one section, is the input to the next section, which reduces this remainder by the same ratio, and so on through the filter. Supply frequency in the rectifier output due to trans-

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† This treatment is strictly correct for circuit 3 only, but gives a good approximation up to a 3% drop for the other circuits.

former and tube unbalance, usually sets a limit to the accuracy of this computation. $1/(2\pi f_h C)$ must be less than $\pi f_h L$ to result in a reduction of ripple in the output. If $1/(2\pi f_h C)$ is greater than $\pi f_h L$, the ripple voltage is increased.

Operation of the rectifier will shift from inductive input to crest rectifier operation if the d-c. load current drops below approximately three times the a-c. ripple current through the first inductor. If the load on a composite filter is suddenly removed, the energy stored if the inductances will flow into the capacitor and remain there until the charge leaks off. Voltages that are many times normal may be generated in this way. The constants should be such that this will not cause capacitor failures, or increase the peak inverse voltage on the tube to a dangerous value.

LOAD

The performance of different types of load fed from various rectifier circuits requires consideration. The output of a rectifier with a filter is the same as pure d-c. in its effect on a load. If the filter contains large inductors and small final capacitors, a change in load causes transient changes in output voltage, similar to those caused by the internal inductance of a d-c. generator.

The unfiltered output of a full-wave or polyphase rectifier acts like any other source of direct current, with the exception that in addition to the d-c. components of voltage and current measured with d-c. meters, harmonic power is applied to the load. On resistive loads, a-c. values of both current and voltage are higher than the d-c. values. (By about 11% for circuit 2, and less for the others.) On inductive loads, the a-c. value of voltage is higher than the d-c., but both values of current are substantially the same.

A back e.m.f. in the load of a filtered rectifier, such as a battery or a d-c. shunt motor, behaves as on any d-c. supply except that if the back e.m.f. exceeds the rectifier no-load voltage, current stops instead of reversing, and power cannot be returned to the line by generator action under these conditions. The peak inverse voltage applied to the tubes is increased by the excess of the back e.m.f. over the no-load voltage, and if large enough to exceed the tube rating, may cause the tubes to arc back.

The action of a back e.m.f. in the load of an unfiltered rectifier, is much the same as the above except that current will continue to flow as the back e.m.f. is increased beyond the no-load rectifier voltage, until the back e.m.f. equals the peak of the a-c. phase voltage, less tube starting voltage. In this respect, a motor or battery acts like an enormous capacitance, and the rectifier changes its operation to that of a crest rectifier.

Energy stored in an inductive load is dissipated without surges when the rectifier power supply is shut off, because current continues to flow through the tube in the normal direction until the stored energy is spent.

If the d-c. circuit is opened, the energy is dissipated at the switch as with any other d-c. supply. Where the capacitance across the open switch is higher than the order of .001 mfd, very high short duration inverse voltages may appear across the tube. In such cases special precautions should be taken to prevent exceeding the tube rating.

A half-wave rectifier working into an inductive load, is a special case due to the high harmonic content of the direct current. The output voltage can not be computed in such cases from Table I. Current flows for more than 180° and less than 360° each cycle, the angle depending on the ratio of inductance to resistance. The calculation of the d-c. and a-c. values of the current is considered on page 16-03 of reference 4 listed in the bibliography on page 32.

MECHANICAL DESIGN

EL Rectifiers are sturdily constructed to withstand mechanical shock and vibration. All tube types are vibration tested under load at .04″ amplitude at 10 to 25 vibrations per second. Some of the tube types are tested to much more severe limits.

Ambient temperatures are no problem as EL Rectifiers will operate over an extremely wide range without noticeable change in characteristics. Lower temperatures than rated ambient increase the filament heating time, whereas higher temperatures than rated endanger the soldered joints in tube sockets and bases. Heat given off by EL Rectifiers is largely radiant and tends to heat surfaces on which it falls. It should be noted that the tantalum anodes are operated at red heat during normal full-load operation for the reason that tantalum "gettering" action is most effective in this temperature range.

Good socket contacts are essential to long life.[15] It should be remembered that one function of the socket is to carry away and radiate the heat which is conducted down the filament leads. Much can be done to radiate this heat and to keep the socket contacts cool by providing large heavy wiring in the filament circuit.

Sufficient room should always be provided in rectifier units to allow insertion of tubes of the maximum over-all length specified in the data sheets.

TUBE VARIATIONS

It is not safe to try a few tubes in a newly designed unit, and if operation is satisfactory, assume that no tube rating is exceeded. The tubes tried may have actual breakdown points much higher than rating. The only safe thing is to carefully calculate, or observe on a calibrated oscilloscope, applied peak inverse voltages and peak currents. Circuits should be such that any tube within any of the limits given in the data sheet will provide satisfactory operation of the unit. Arc drop and starting voltage are the characteristics that vary most throughout life. Arc drop variations have been discussed under "Tube Characteristics".

Starting voltage is usually highest after periods of lit filament with no load, and decreases during the first few seconds of load.

LIFE EXPECTANCY—RECTIFIERS

As with mechanical devices, tubes, if properly made and well used, will last many years. In EL Rectifier tubes, one of the common limits to tube life, namely, evaporation of the active material from the cathode, has been so completely reduced that it is no longer a factor. As a result EL Rectifiers, when properly used, usually fail from some chance cause before burning out or using up any tube element. Either some occasional circuit condition does slight damage which ultimately builds up to a failure, or some part within the tube continues to give off minute traces of contaminating gas during operation which are not detectable for thousands of hours, but which ultimately cause failure. At present no life can be set beyond which a tube could not possibly live. Operating conditions are a determining factor in tube life.

The following rules, while not complete as yet, are the generalized results of experience attained with many actual installations and life tests:

1. An accidental cold start, i.e., turning on load and filament voltage together, consumes an appreciable amount of life. The higher the voltage or heavier the current, the more important this loss of life becomes.
2. Operating with filament voltage beyond ± 5% of rating reduces life unless special ratings have been observed.
3. Exceeding rated peak inverse voltage will cause either immediate or rapid tube failure.
4. Operating at frequencies above 350 cycles, with tubes having no upper frequency limit stated on the data sheet or under conditions of high initial inverse voltage, as a back rectifier with a grid control rectifier, may decrease life, the amount depending on the circuit and tube. In the latter case reference should be made to page 23 for proper precautions in circuit design to avoid short tube life from this cause.

TABLE I

RECTIFIER CIRCUIT CONSTANTS

Assuming Ideal Transformers and Rectifiers

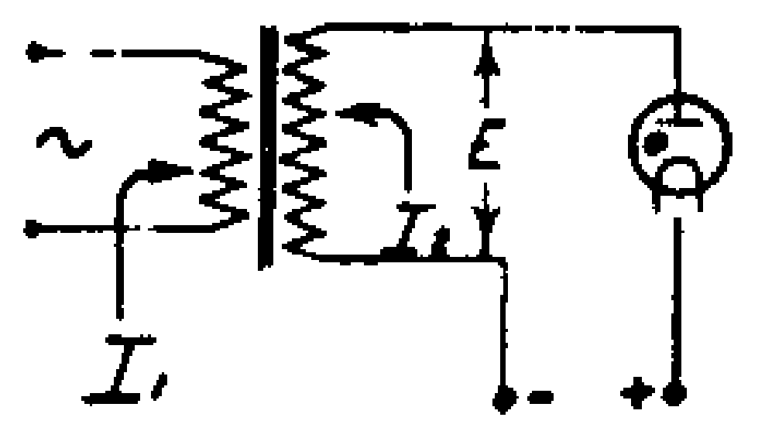


FIG. 1

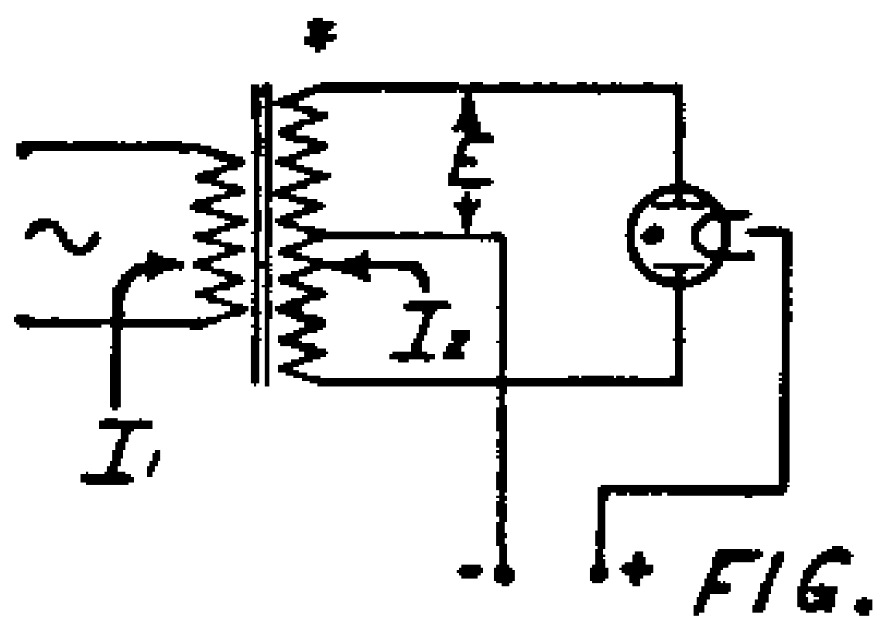


FIG. 2

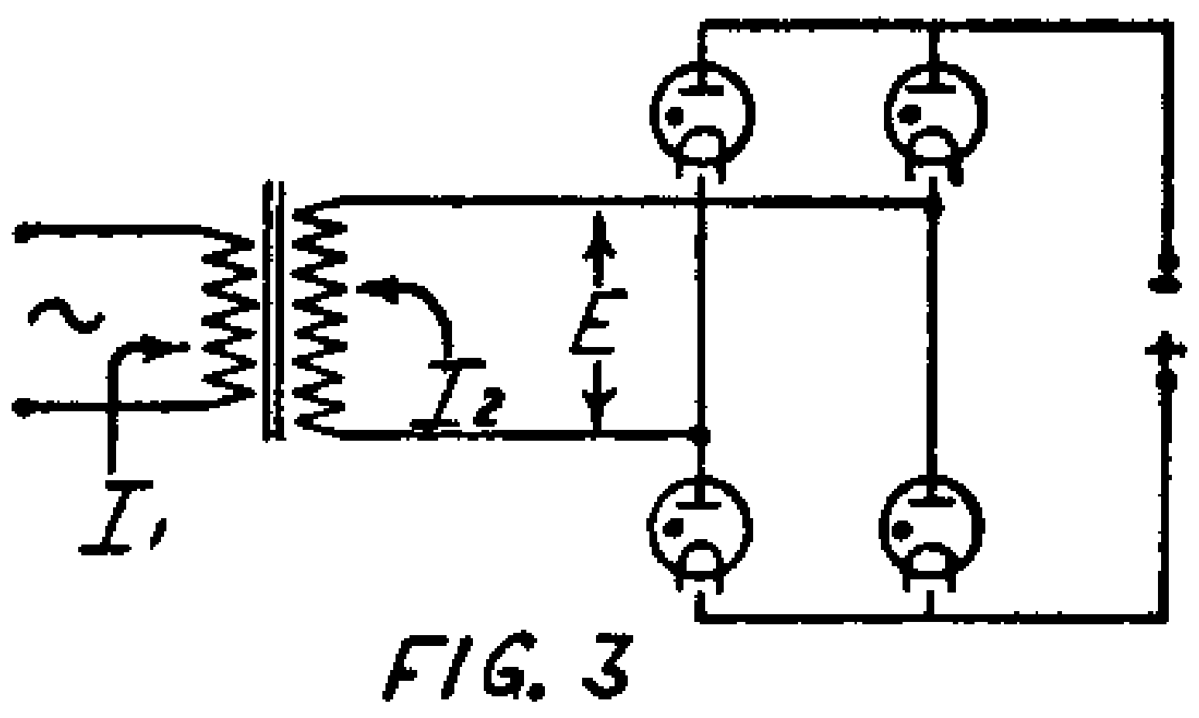


FIG. 3

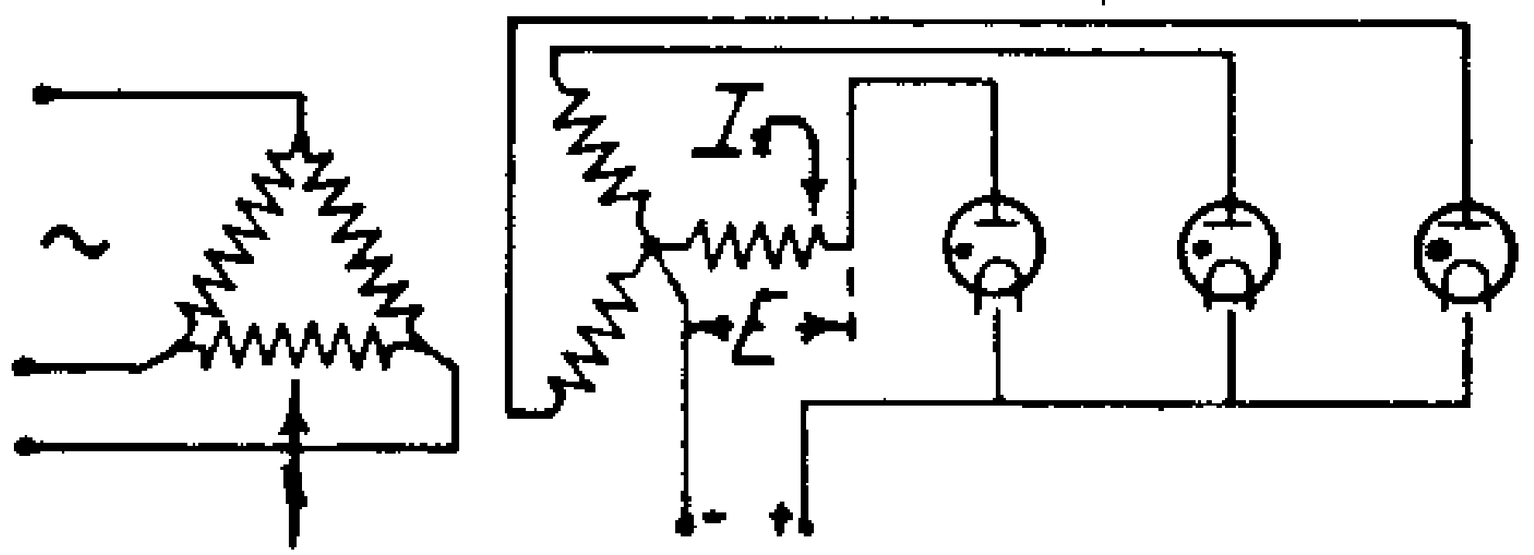


FIG. 4

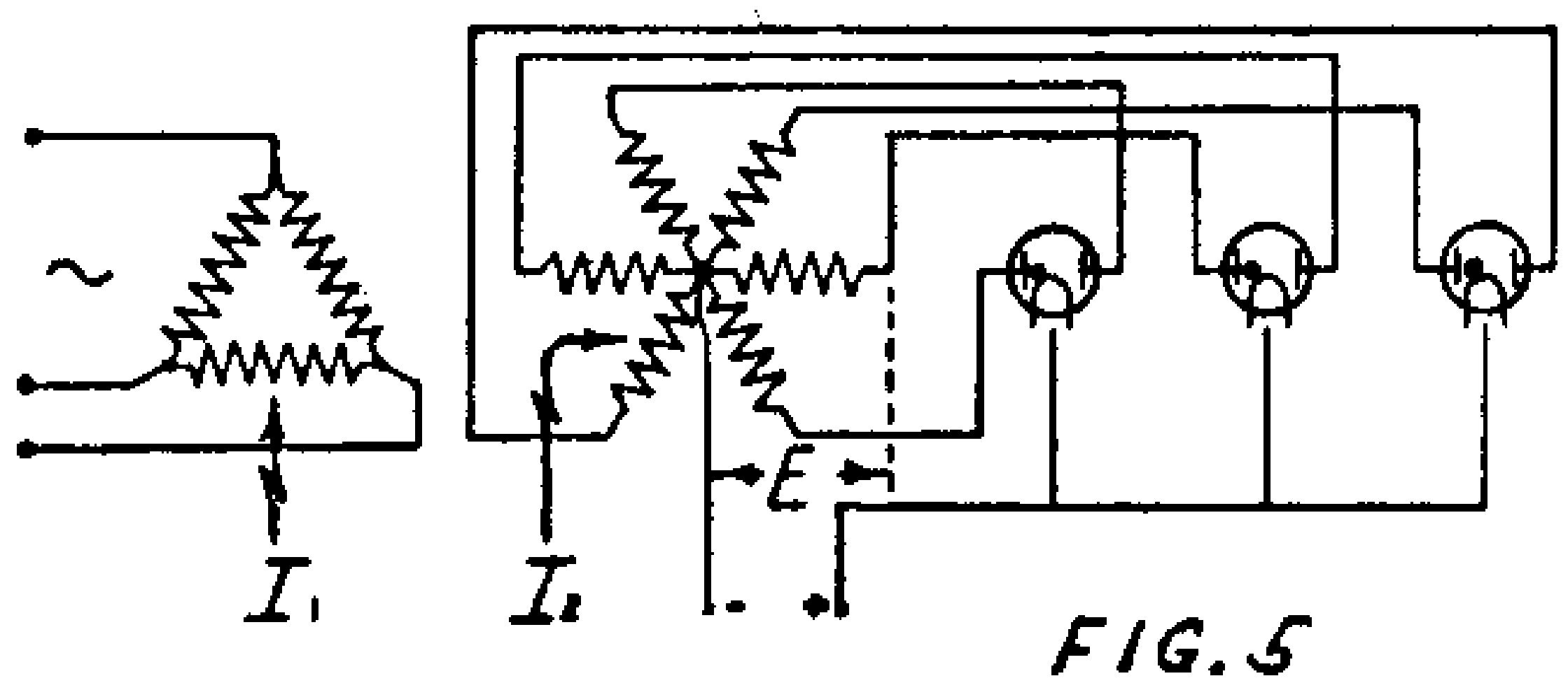


FIG. 5

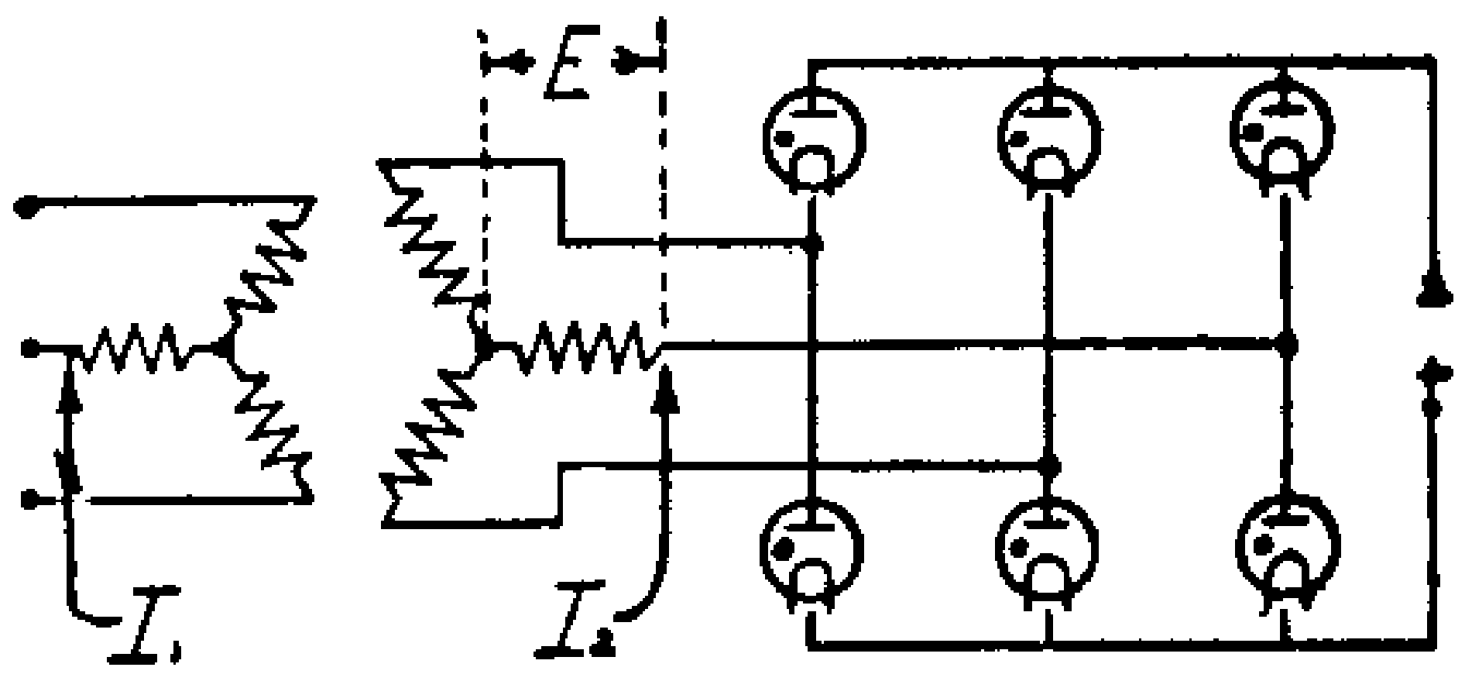


FIG. 6

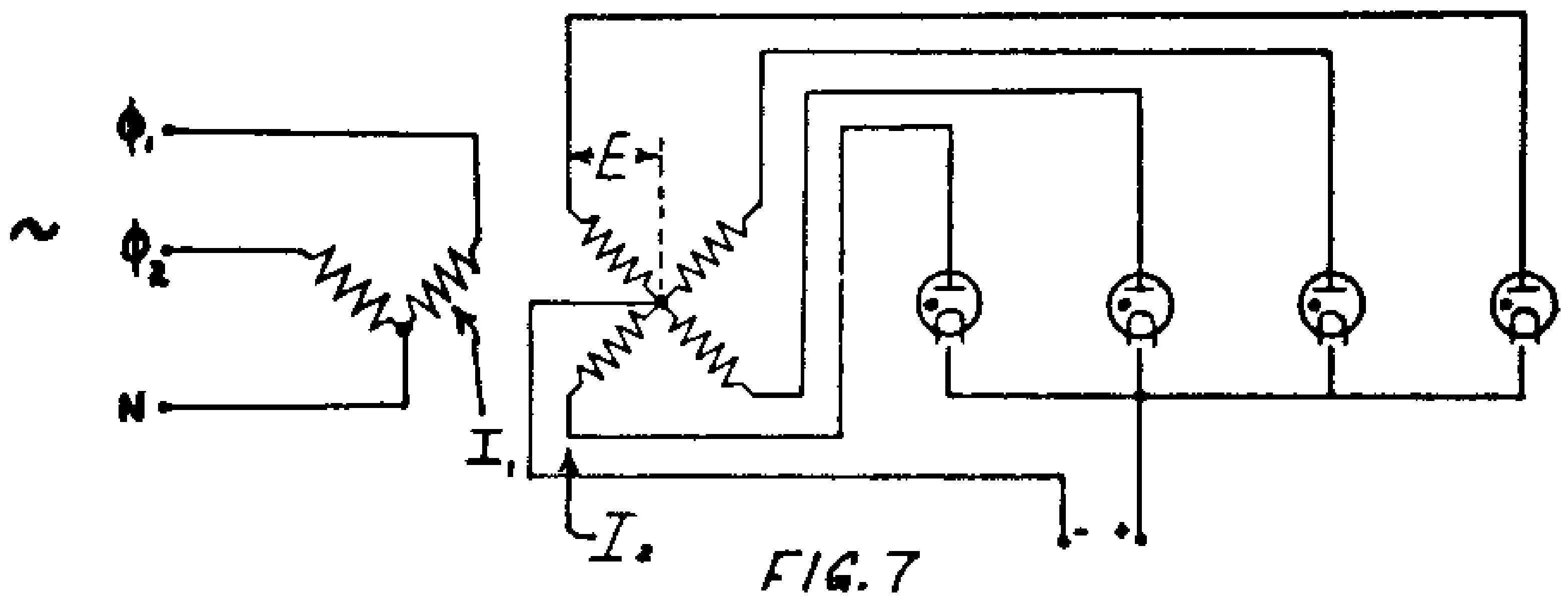


FIG. 7

SYMBOLS

V = D-c. output volts,

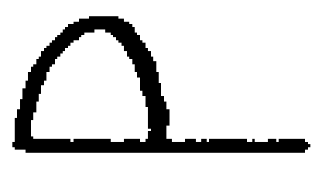
A = Total d-c. output amperes,

f = Supply frequency,

$$N = \frac{\text{Turns in winding marked E.}}{\text{Turns in winding marked } I_1\text{.}}$$

A-c. voltages and currents are r.m.s. or effective a-c. values.

D-c. voltages and currents are average or d-c meter values.

CIRCUIT NOS.		Fig. 1	Fig. 2	Fig. 3	Fig. 4	Fig. 5	Fig. 6	Fig. 7
A-c. Plate Volts	E	2.22V	1.11V	1.11V	0.854V	0.740V	0.427V	0.785V
A-c. Secondary Current	I_2							
Resistive load		1.57A	0.785A	1.11A	0.587A	0.409A	0.817A	0.503A
Inductive load		—	0.707A	A	0.577A	0.408A	0.815A	0.500A
A-c. Primary Current	I_1							
Resistive load		*1.21AN	1.11AN	1.11AN	0.480AN	0.579AN	0.817AN	0.711AN
Inductive load		—	AN	AN	0.472AN	0.577AN	0.815AN	0.707AN
Peak Inverse Volts	PIV	3.14V	3.14V	1.57V	2.09V	2.09V	1.05V	2.22V
Average D-c. Anode Current		A	0.5A	0.5A	0.333A	0.167A	0.333A	0.25A
Peak Anode Current								
Resistive load		3.14A	1.57A	1.57A	1.21A	1.04A	1.04A	1.11A
Inductive load		—	A	A	A	A	A	A
Effective Phases	p	1	2	2	3	6	6	4
Commutation Regulation Coef	K							
Resistive load		—	0.000	0.000	0.286	0.866	0.866	0.500
Inductive load		—	0.318	0.636	0.477	0.954	0.954	0.637
Output Voltage Wave Shape								
Major Ripple Frequency	f_h	f	2f	2f	3f	6f	6f	4f
A-c. Ripple Voltage	E_h	1.11V	0.47V	0.47V	0.18V	0.040V	0.040V	0.094V

* Transformer magnetizing current and core losses are important and must be added to the primary current in this circuit.

5. Tube life depends on the unit as to which characteristic necessitates discarding, and how far it can deteriorate before affecting performance. Usually, high arc drop is the reason for failure, though occasionally a filament burns out or protective apparatus fails.
6. A defective tube or circuit condition will nearly always cause failure within 3,000 hours.

Thus far, no uniformly satisfactory method of anticipating failure has been found. Replacing tubes periodically is not advisable as the probability of a tube having a long life often improves after about 3,000 hours of operation. In some units, the tube gives visual evidence, by which operators, after a little experience, can anticipate a failure. Often a regular program of observing arc drop while the tube is in service in the unit by means of a cathode ray oscilloscope* will anticipate most failures.

GRID CONTROL RECTIFIERS USED AS DIODES

Grid control rectifiers may be used as diodes where anode current or voltage ratings make this desirable. The grid is preferably connected to the cathode through a current limiting resistance. To assure a low anode starting voltage the grid may be connected to a voltage divider between anode and cathode, or to a resistance-capacitance network similarly connected to provide the grid with an a-c. voltage which leads in phase the anode voltage. In both cases the instantaneous grid voltage should be limited to the maximum negative grid voltage rating.

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* Connecting directly from tube anode and cathode to the oscilloscope deflection plates with the internal blocking capacitor removed. See reference 9 listed in the bibliography.

DESIGN OF GRID CONTROL RECTIFIER UNIT

SINCE a control rectifier tube, sometimes called a thyratron, is a half wave rectifier with the addition of a grid the application and design information pertaining to EL Rectifiers also applies to EL control tubes.

If the anode of a control tube is made positive, a change of grid potential of 4 volts or less will permit or prevent the start of conduction. After starting, the drop across the tube is reduced to the arc drop of 5 to 12 volts and behaves as previously described for rectifiers. With an a-c anode supply the arc is extinguished and control is regained each cycle while the anode is negative. By controlling the point of starting in each cycle the average output voltage may be regulated from zero to maximum. The current that results from this voltage is determined by the load and circuit connection. The sketches in Fig. 1 depict these conditions.

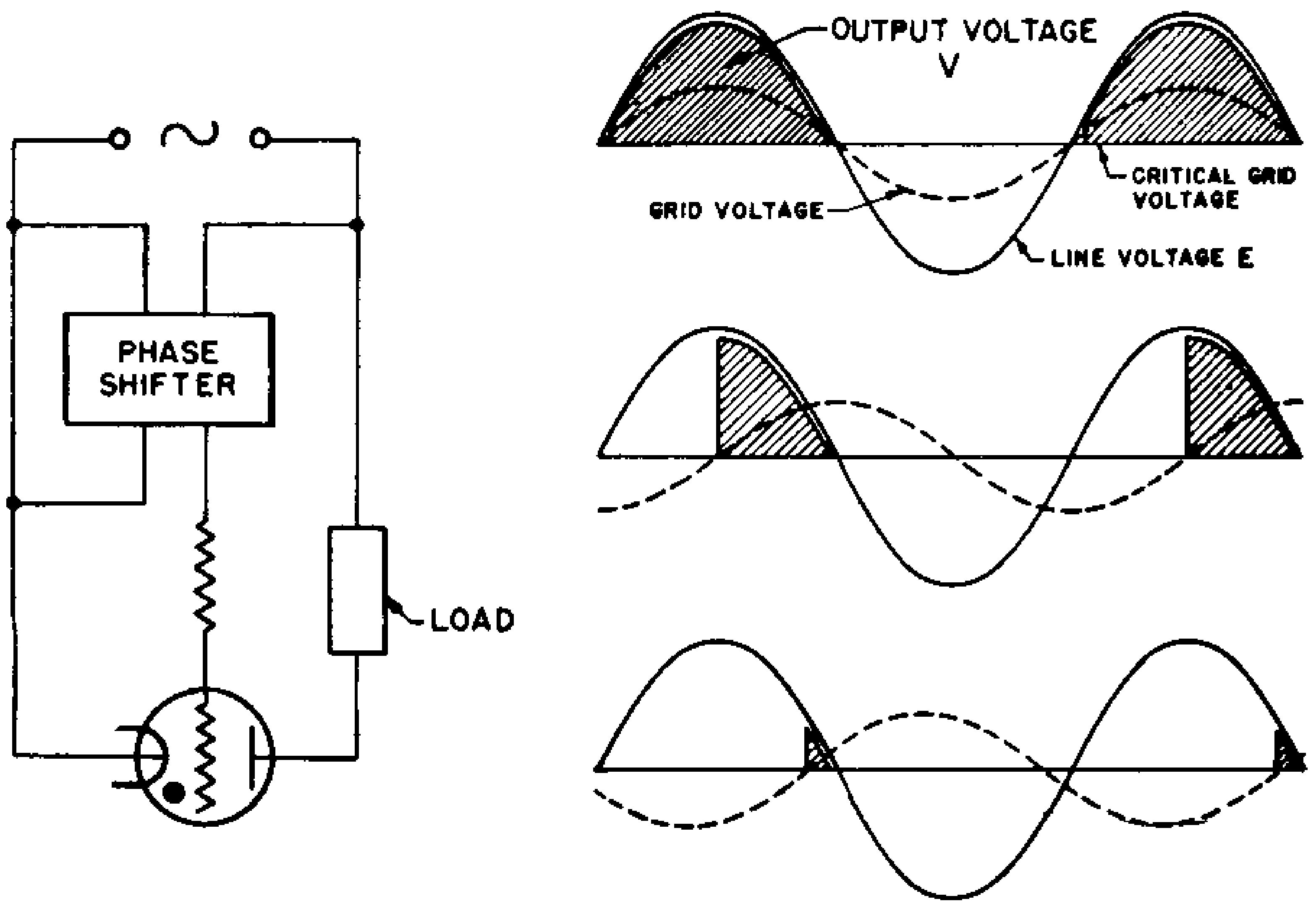


Figure 1

Control Tube Ratings

In addition to its rectifier ratings, a control rectifier has the following ratings:[8]

(1) PEAK FORWARD VOLTAGE

There is a limit to the instantaneous positive anode voltage relative to cathode that may be applied without danger of loss of grid control. This is called the maximum peak forward voltage rating. No permanent injury to the tube results from exceeding this rating but the uncontrolled power may be objectionable.

(2) MAXIMUM NEGATIVE GRID VOLTAGE

Actual loss of grid control is caused by a discharge originating between the grid and anode. The voltage between these electrodes is greater than the peak forward voltage by the amount of negative grid voltage. For this reason a maximum negative grid voltage rating is specified. Within limits a greater negative grid voltage may be applied if the peak forward voltage is correspondingly reduced.

(3) MAXIMUM COMMUTATION FACTOR

During current conduction ions are present in the tube roughly in proportion to the current flowing. In some circuits high inverse voltage is applied immediately after current conduction ceases each cycle. Initial inverse voltage, as this negative anode voltage is called, will attract any ions to the anode with enough velocity to sputter anode material and cause gas clean-up unless precautions are taken to provide a few microseconds to allow the ions to disappear before high voltage is applied (see reference 7 in bibliography). The critical time necessary is best specified by limiting the product of the rate of change of current in amperes per microsecond times the rate of application of initial inverse voltage in volts per microsecond. It is conventional to average the voltage rate over the first 200 volts.

Since the factor varies approximately as the fourth power of the magnitude of initial inverse voltage, the maximum commutation factor rating of a particular tube type for other values of initial inverse voltage than that stated on the data sheet may be determined by multiplying the data sheet value by the fourth power of the ratio of the stated initial inverse voltage divided by the maximum initial inverse voltage (maximum commutating voltage) to be experienced.

(4) MAXIMUM GRID CURRENT

A low impedance grid circuit may under certain conditions impair life by drawing enough current to cause destructive ion bombardment. A grid circuit which each cycle draws more than 1.0 ma to the positive grid at the same time that high inverse voltage is applied to the anode shortens life by creating enough ions to bombard the anode. It is also possible to affect life if the circuit draws more than 10 ma to the negative grid during the anode current conduction period.

A current limiting series resistance is usually connected directly at the grid of the tube.

(5) ANODE CURRENT RATING

In connection with the application of grid control tubes, high peak currents are more often encountered. For high peak current applications, it is important to measure the maximum oscillograph peak current. This supplements the discussion of anode current rating of rectifiers on page 6.

Control Tube Characteristics

The rectifier characteristics apply to control tubes. In addition the instantaneous grid power required for dependable control is specified by:

(1) CRITICAL GRID VOLTAGE

The critical grid voltage is the instantaneous grid voltage relative to the cathode or filament center tap that is necessary to prevent conduction at any given positive anode voltage. The critical grid voltage varies with time since the last conducting period and the history of the particular tube (short circuits; lit filament without load; cold starts; cathode activity and other factors). When all of these factors are taken into consideration for the entire tube life a range is found (given in the data sheets for each tube type, usually less than ±1.5V) above which all EL control tubes will always fire and below which no EL control tube will ever fire.

The critical grid voltage to start the first cycle of conduction differs from the critical grid voltage on cycles that follow a conduction cycle. This effect varies between tubes and on any one tube is increased at heavier loads or higher frequencies. Typical 60 cycle variations are from 0.05 to 0.5 volts. (This should not be confused with grid circuit conditions, discussed later, which may cause a similar result.)

Typical breakdown or firing point curves showing the variation in critical grid voltage with anode voltage are given for the various tubes in the data sheets. These curves are taken with d-c. anode and grid voltages. With a-c. plate voltages, phasing of the filament may be such that this critical grid voltage may vary slightly from the above since some filament voltage is effectively in the grid circuit.

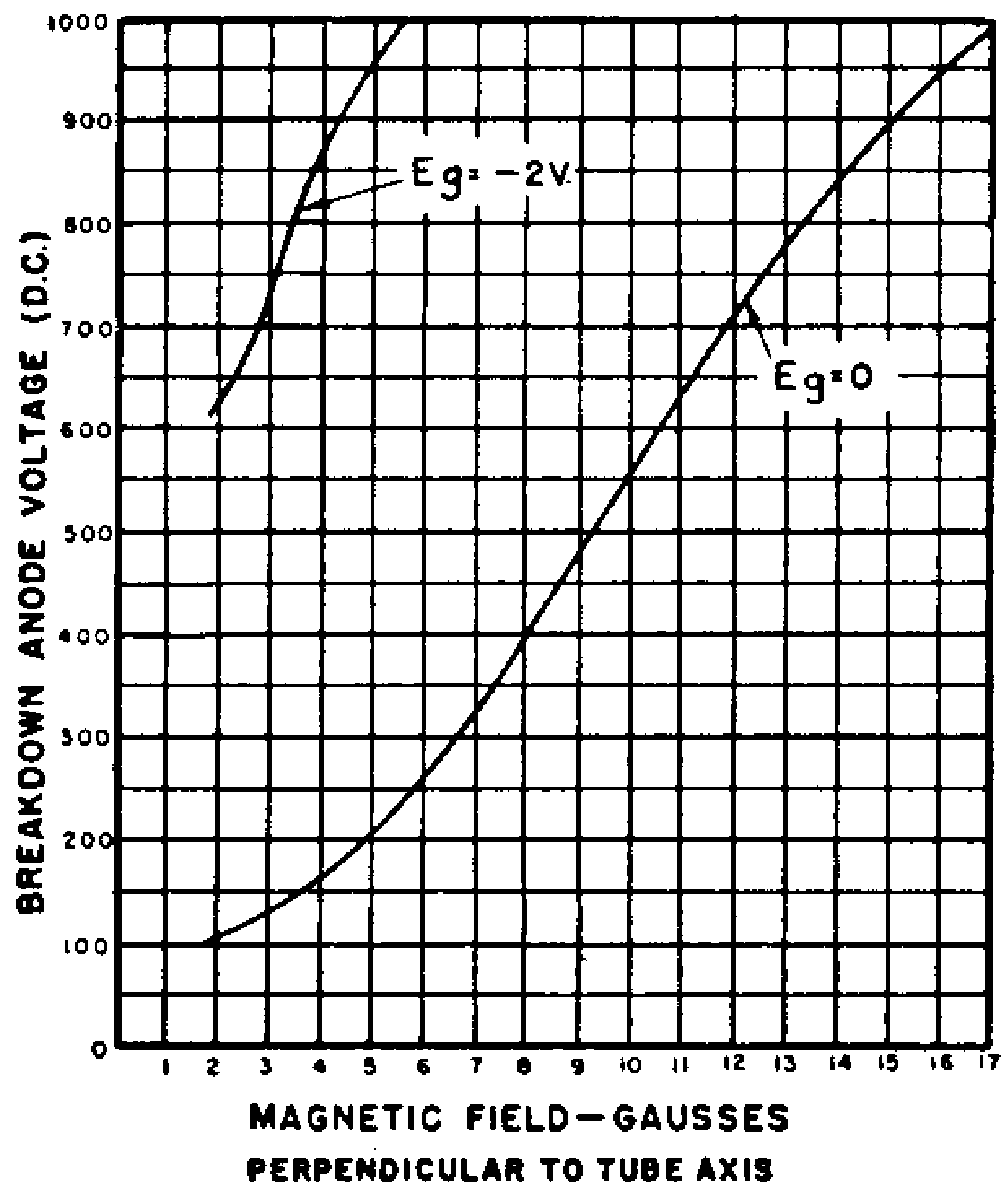


Figure 2a

The critical grid voltage is affected to some

extent by magnetic fields in the cathode anode region of the tube. To indicate the order of magnitude the curves in Fig. 2a & 2b give the test results on a representative EL C6J tube.

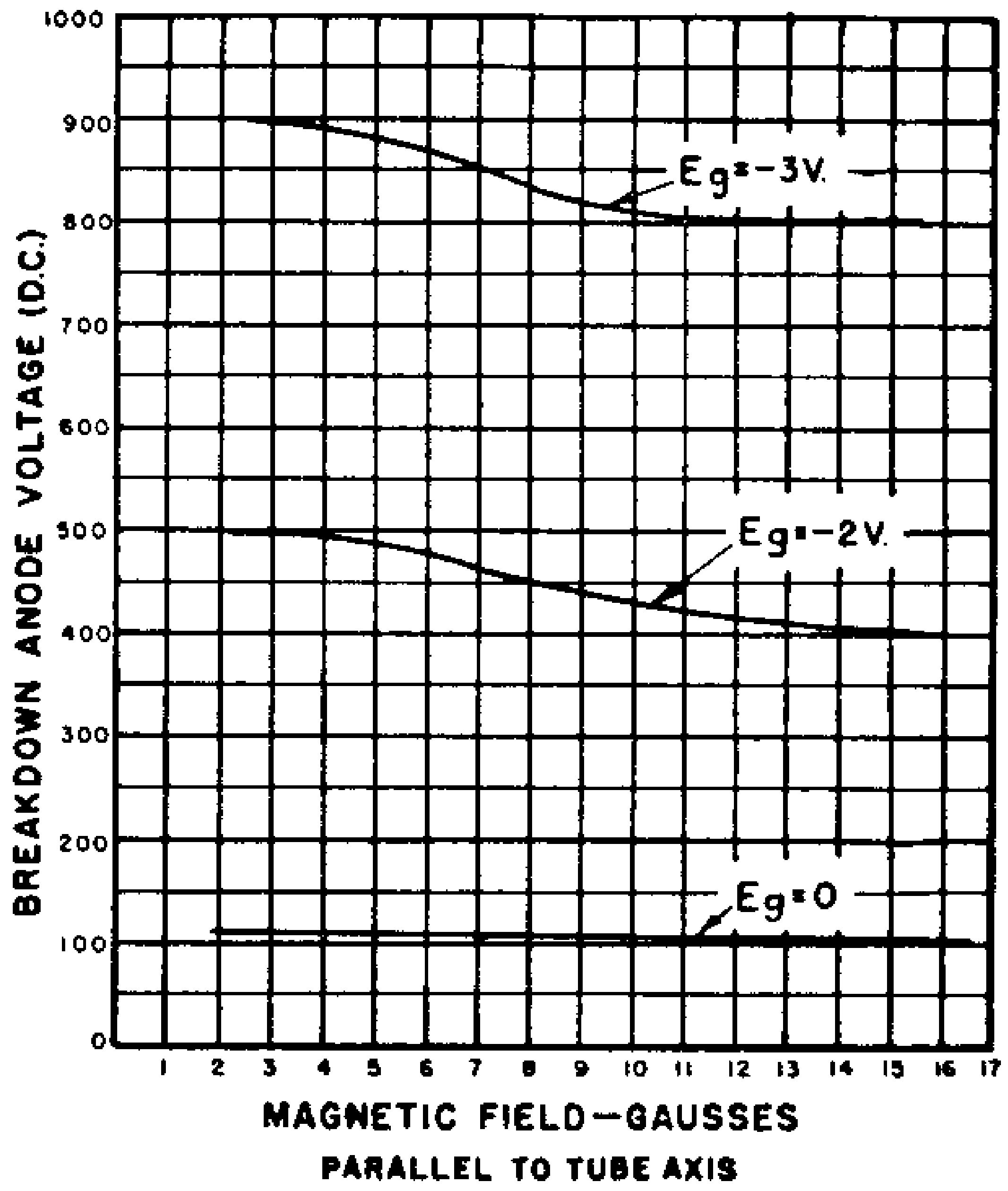


Figure 2b

(2) STARTING VOLTAGE

The breakdown curve indicates a range where anode breakdown voltage does not change materially with change of grid voltage (usually near +4 volts). This anode voltage is called the starting voltage. Below this, the tube can be started at anode voltages as low as 10-15 volts by the application of sufficient excess positive grid drive.

(3) CRITICAL GRID CURRENT

As the critical grid voltage is approached a minute grid current flows in a direction to produce a drop in the grid resistor making the actual grid potential more positive than the applied grid voltage. This is called the critical grid current and is considered a negative current in this direction. It is measured by noting the difference in apparent critical grid voltage with and without a large series resistor. The critical grid current varies between tubes and with anode voltage, operating conditions, tube temperature, and frequency, but never exceeds a few microamperes. Maximum values for 60 cycle operation are given in the data sheets on EL Control Rectifiers. These values allow for the worst conditions with any tube throughout its full life. These are more conservative ratings than measured "preconduction" currents which specify only the critical grid current on the first conducting cycle.

When the tube must be fired at anode voltages below the rated starting voltage, the critical grid current is reversed and its magnitude increased many fold. The following curve illustrates the variation in critical grid current with anode voltage for a specific EL C6J tube.

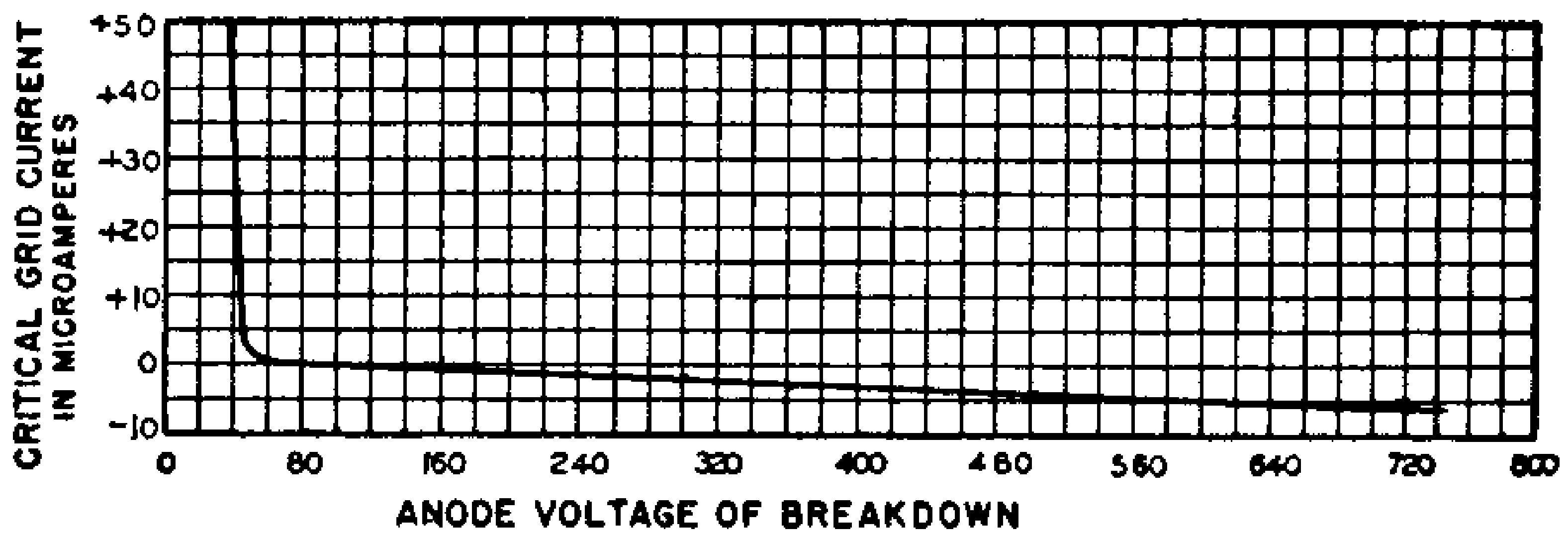
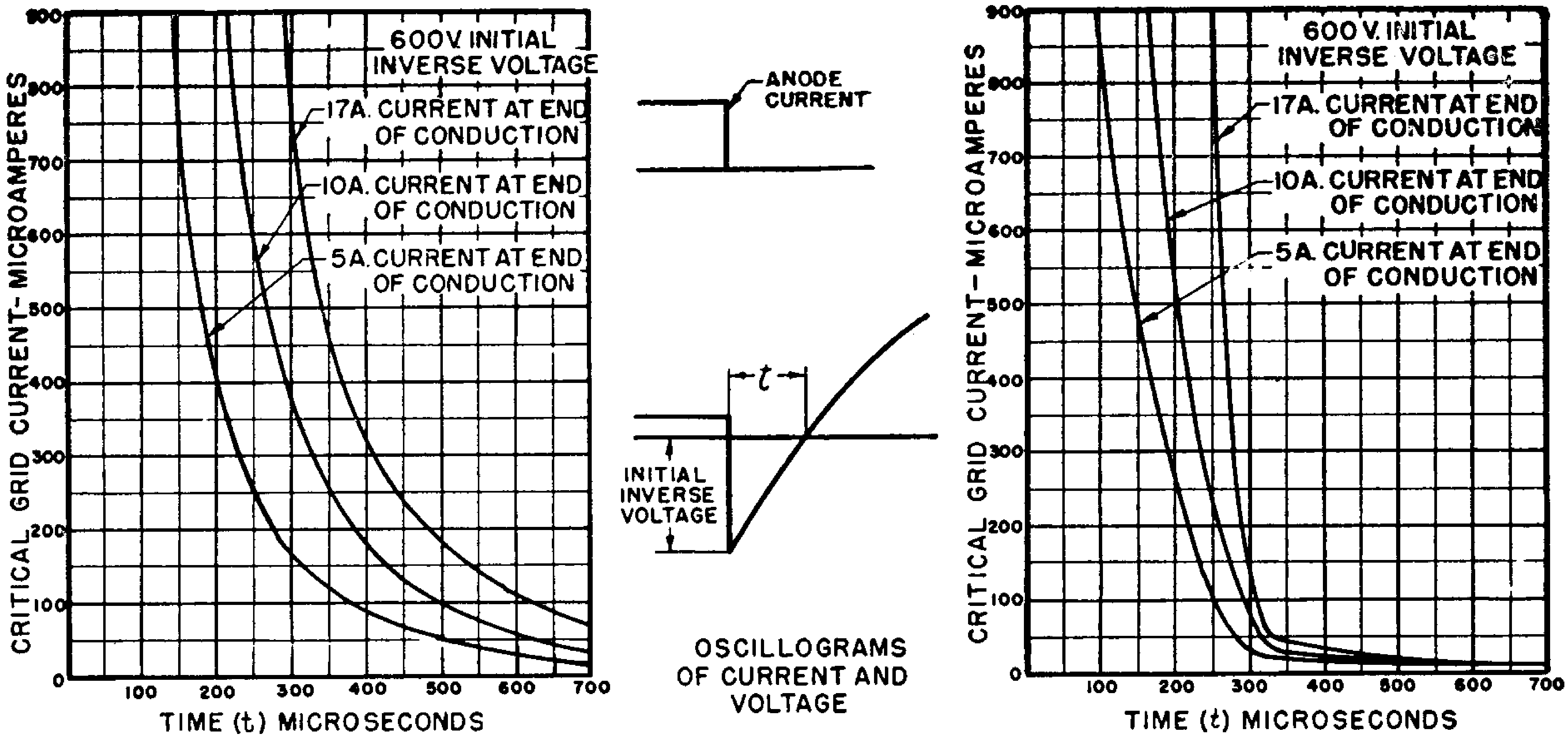


Figure 3

The critical grid current is a function of deionizing conditions as will be apparent from the consideration of deionization time. Therefore, the critical grid current immediately after each conduction cycle is greater than the grid current before the first cycle of conduction.

(4) DEIONIZATION TIME

The time required for the grid to regain control after a period of current conduction is a function of anode voltage, grid voltage and current magnitudes. Incipient failure to deionize shows up as an apparent increase in critical grid current. The following curves on a typical EL C6J tube indicate the nature of these variations.



C6J TUBE

C6M TUBE

Figure 4

The ratings given in the data sheet are rough indications of the relative speed of deionization of the various tube types. For certain applications where shorter deionization time is desired several special types of gas-filled grid control tubes are available with shorter deionization times as indicated in Figure 4. These curves are shown for 600 volts on the anode. Similar curves at other anode voltages do not vary significantly from those shown.

(5) IONIZING TIME

With anode voltage above the data sheet starting voltage, from 0.5 to 20 microseconds are required to start the discharge. The lower range is for large grid overvoltages, i.e. grid more positive than the critical grid volts. Anode voltages below the starting voltage may require up to 2,000 microseconds to fire depending largely on grid circuit impedance and grid overvoltage. Tests made on representative EL C6J tubes with 25 volts anode voltage and 15 volt positive grid pulses indicated that most tubes ionized in less than 50 microseconds.

Power Circuits

(1) D-C. OUTPUT[14]

Control rectifiers are used for d-c. loads in the usual rectifier circuits as listed in Table I. The output wave shape, transformer currents and voltages at maximum output are the same as for a rectifier. As firing is delayed the output voltage decreases, its ripple component increases, and the primary power factor angle becomes more lagging. These effects may be analyzed more fully by considering the different types of load separately.

(a) Resistive Load

The single phase full wave circuit of Figure 2, Table I, may be taken as an example If the load is resistive the output wave shape is as follows.

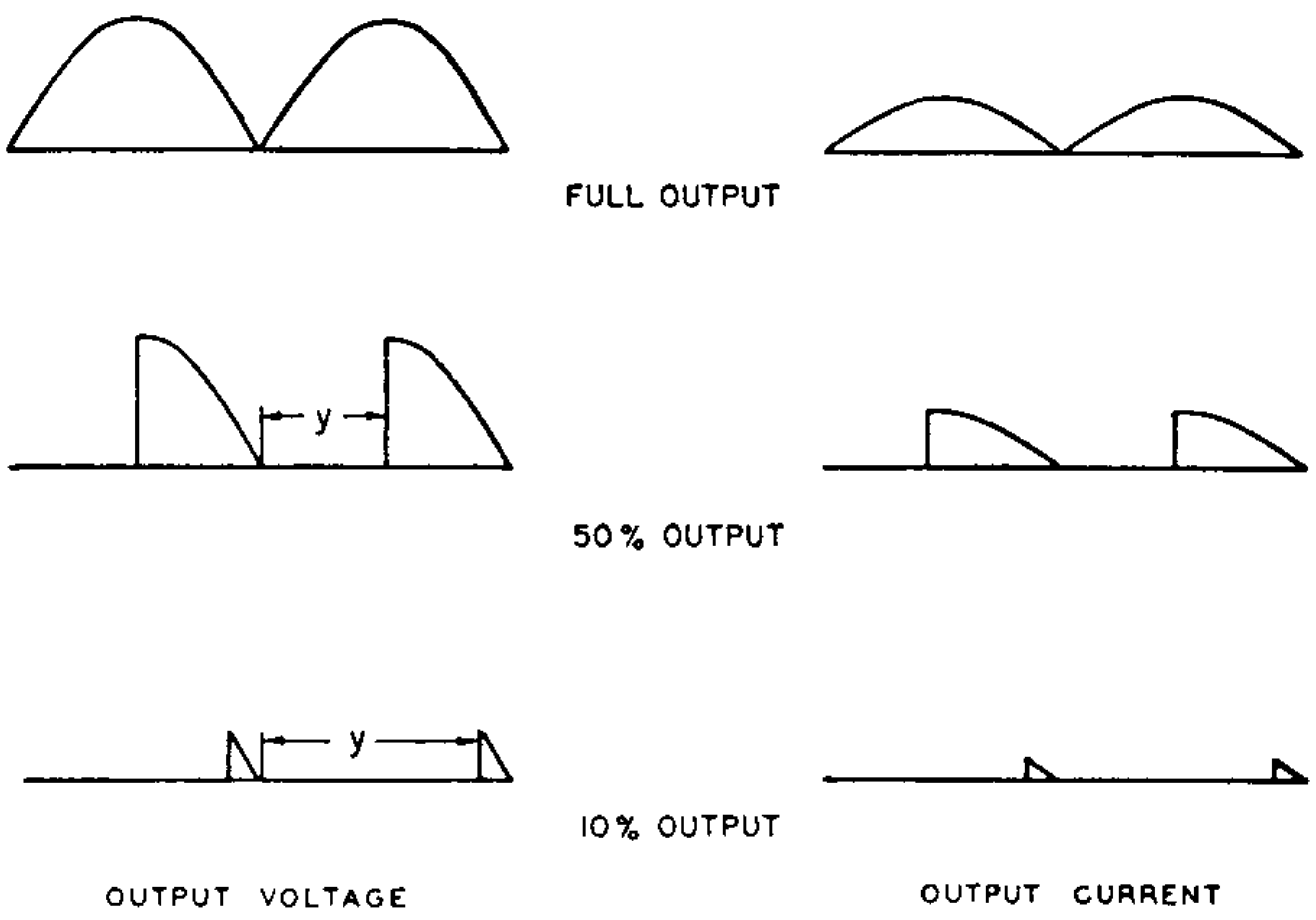


Figure 5

Assuming ideal transformers and rectifiers the d-c. meter value of output voltage is:

$$V = \tfrac{1}{2}\,\mathrm{Vm}\,(1 + \mathrm{Cosine}\ y)$$

where y = angle during which firing is delayed by the grids, Vm = max. d-c. output voltage or the value calculated for the circuit as a straight rectifier.

This equation also applies to half wave circuits.

(b) Inductive Load[13]

If the load is inductive enough for the peak ripple current to be less than ½ the average d-c. current the output current becomes continuous. In this case, once a tube has fired, the energy stored in the inductance during the positive half cycle causes the inductance to generate whatever voltage is necessary to overcome the negative supply voltage and continue the current flow through the conducting tube and load circuit after the end of each positive half cycle. With an inductive load and ideal transformers the output wave shapes are shown in Figure 6. Actually due to transformer reactance there is a period of overlap during which both tubes conduct simultaneously, and load current is commutated from one tube to the other.

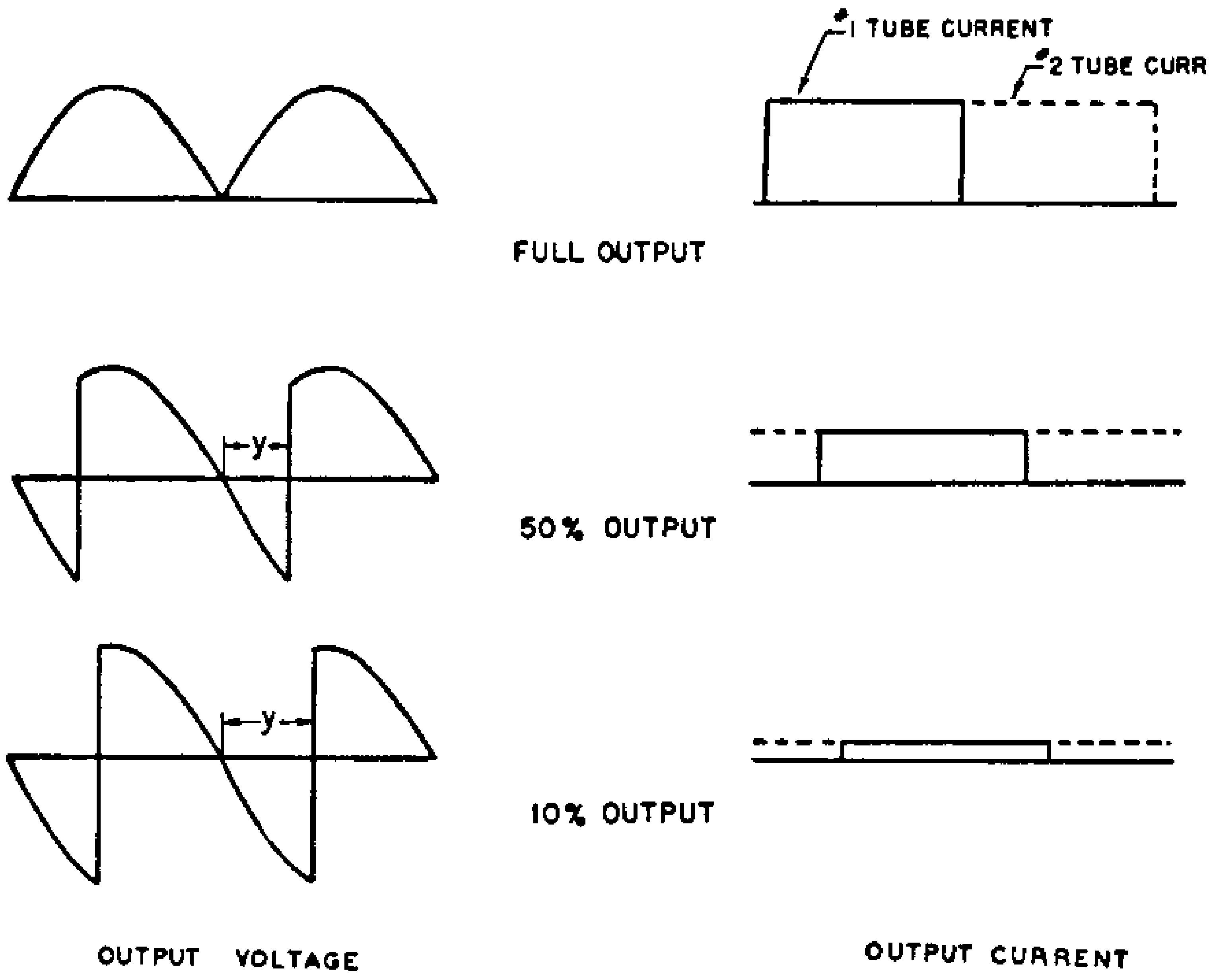


Figure 6

In the ideal case the d-c. meter value of the output voltage neglecting the small effect of overlap is:

$$V = \mathrm{Vm}\,(\mathrm{Cosine}\ y)$$

This equation also applies to polyphase units and bridge circuits when the load is inductive enough to force continuous output current. Expressed graphically the output voltage varies with grid delay angle thus:

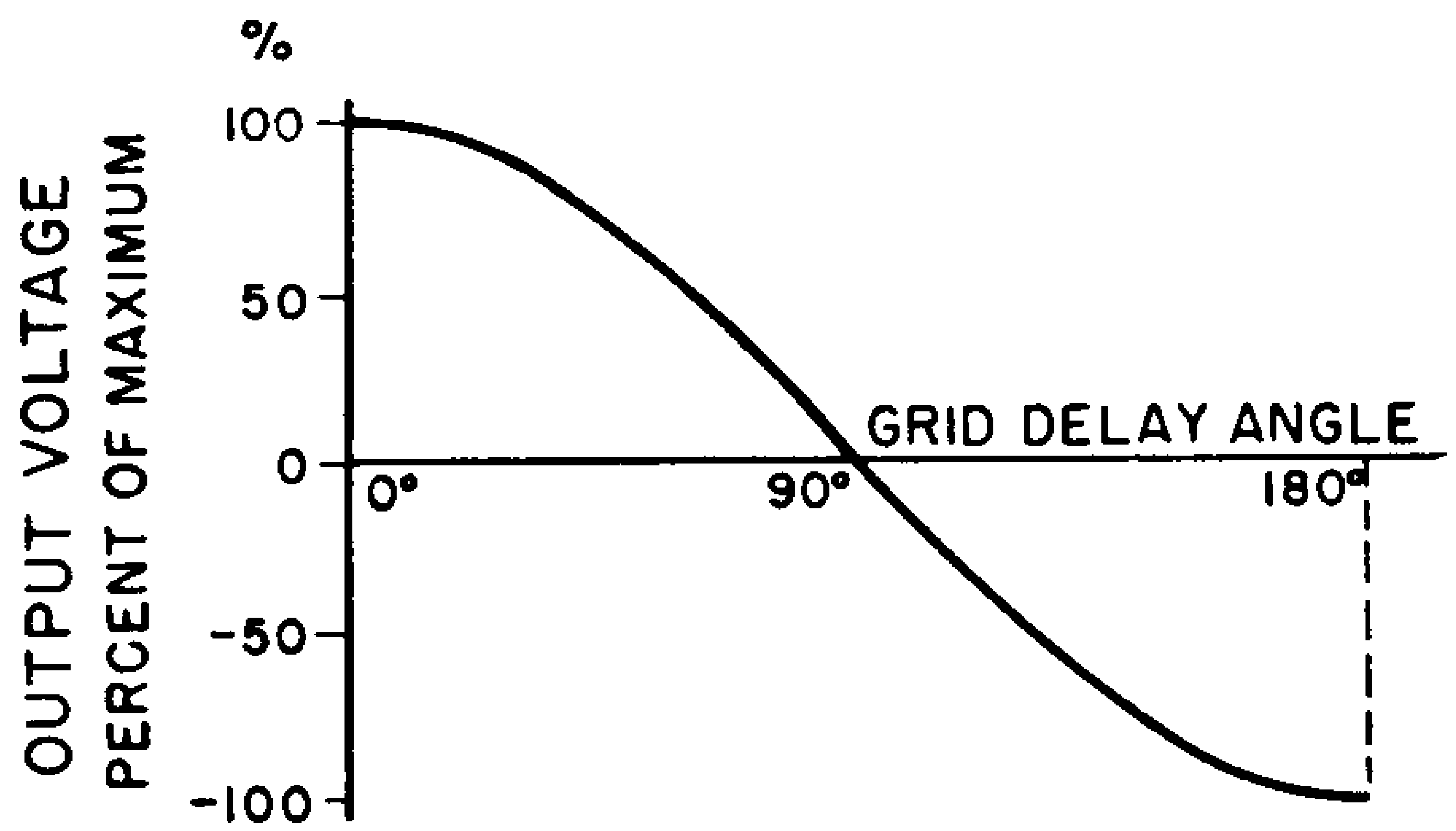


Figure 7

The negative output voltage range in Figure 7 occurs with grid retard greater than 90°, since the negative area under the output voltage curve exceeds the positive. Such operation requires a source of d-c. voltage to force current flow and constitutes the region where the unit operates as an inverter, supplying power to the a-c. lines.

The peak forward voltage applied to the tubes by a full wave single phase circuit is 1.41 E (E = r.m.s. anode to center tap voltage) with resistive or capacitive loads and double this for inductive loads. An allowance should be added for high line voltage and transient disturbances to find the required tube peak forward voltage rating.

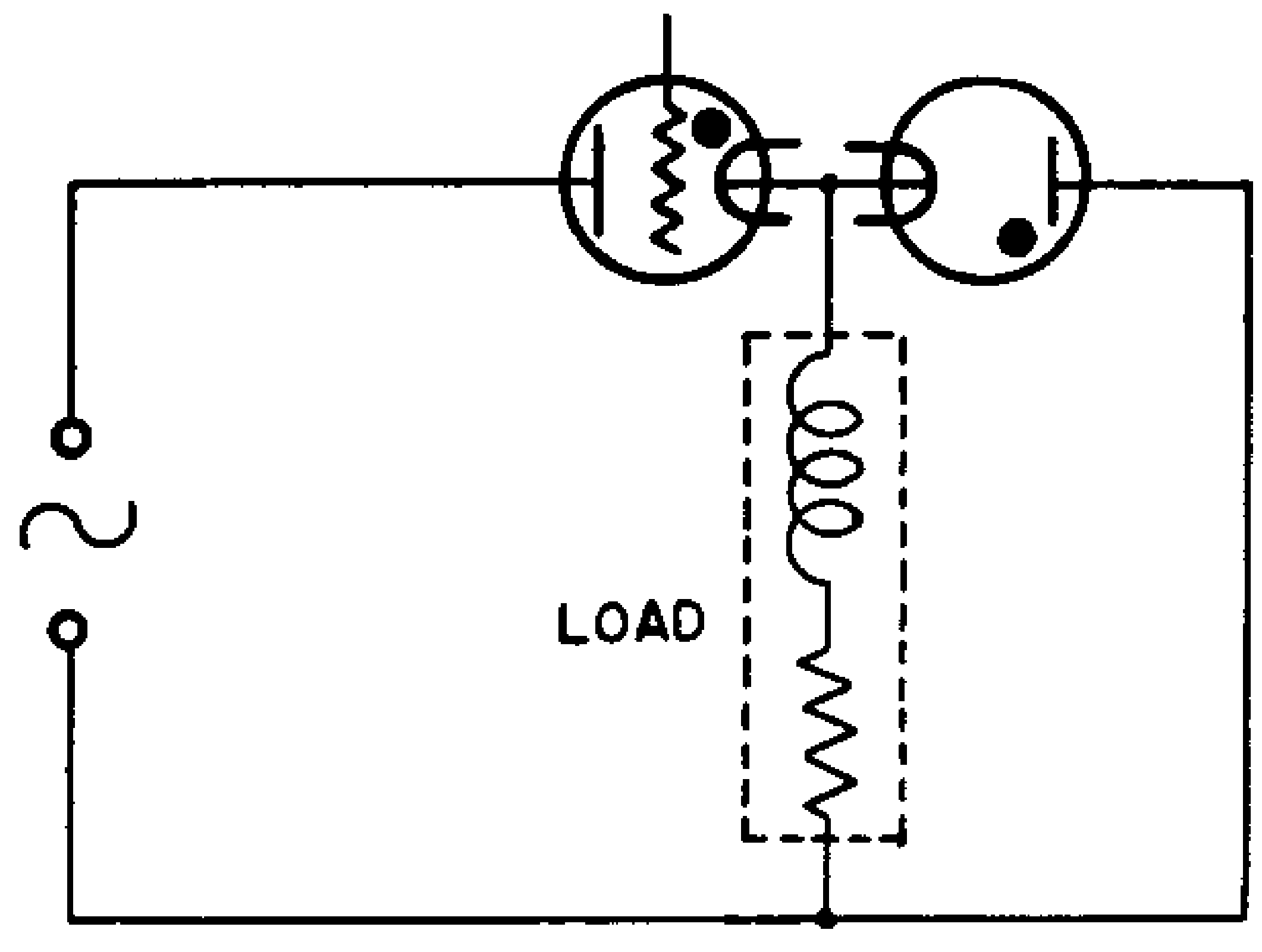


Figure 8

The above figure shows an additional circuit often used when the load is so highly inductive that current is always continuous. The load voltage is under control of the single grid.

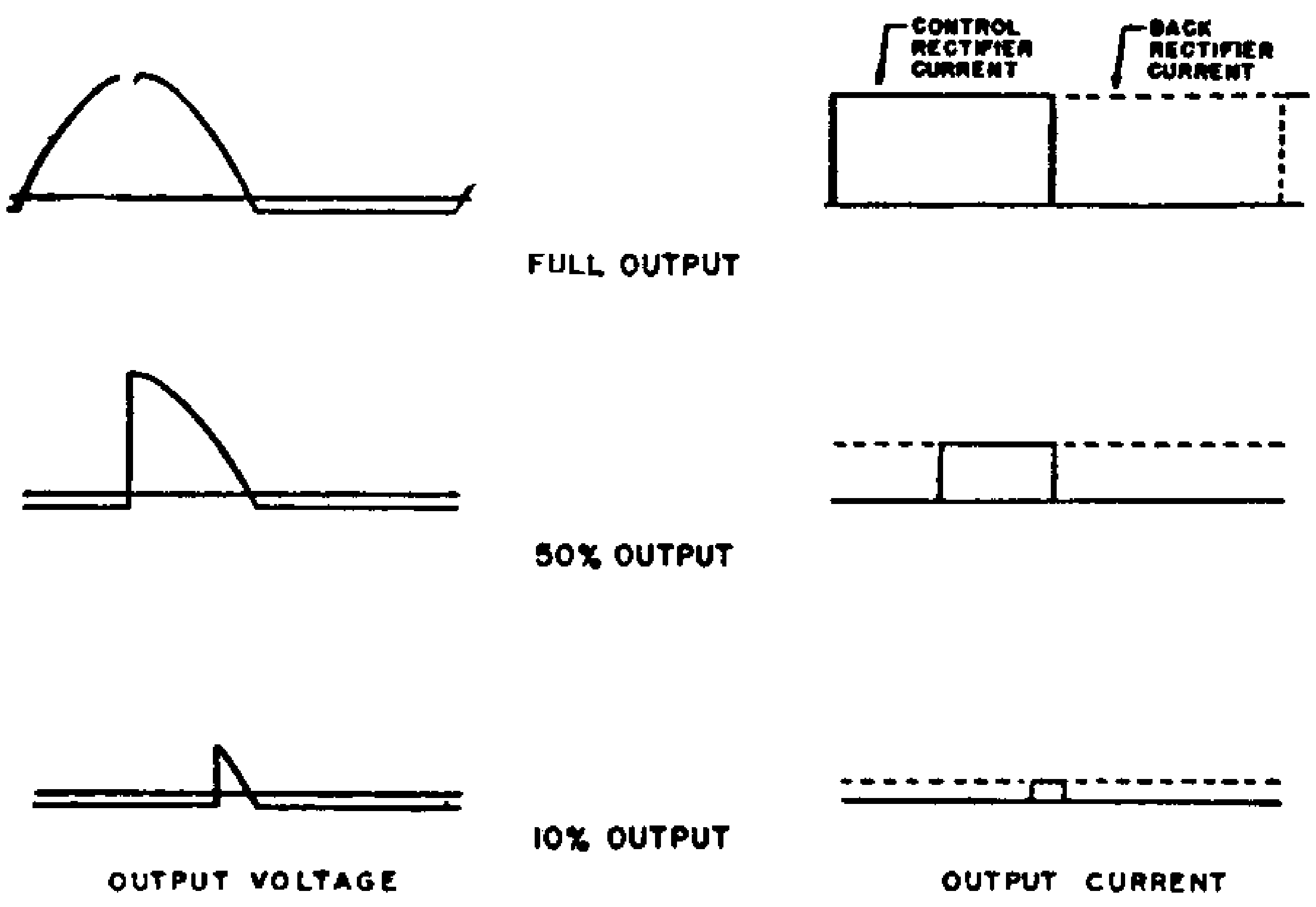


Figure 9

Peak forward voltage applied to the grid control tube and peak inverse voltage applied to the rectifier is 1.41 a-c. line voltage. Maximum output voltage is a-c. line voltage divided by 2.2 less tube drop. The d-c. meter value of current through the control tube and also that through the rectifier at full output is ½ the d-c. load current. See Fig. 9.

(c) Capacitive Load

A capacitive load on a grid control rectifier circuit is quite practical, however, it is suggested reference be made to the discussion under Rectifier Circuit Design regarding the limitation of peak tube currents, by transformer leakage inductance or the addition of series inductance.

(2) A-C. OUTPUT[14]

An a-c. load may be controlled by one of the circuits shown in Figures 10 to 15.

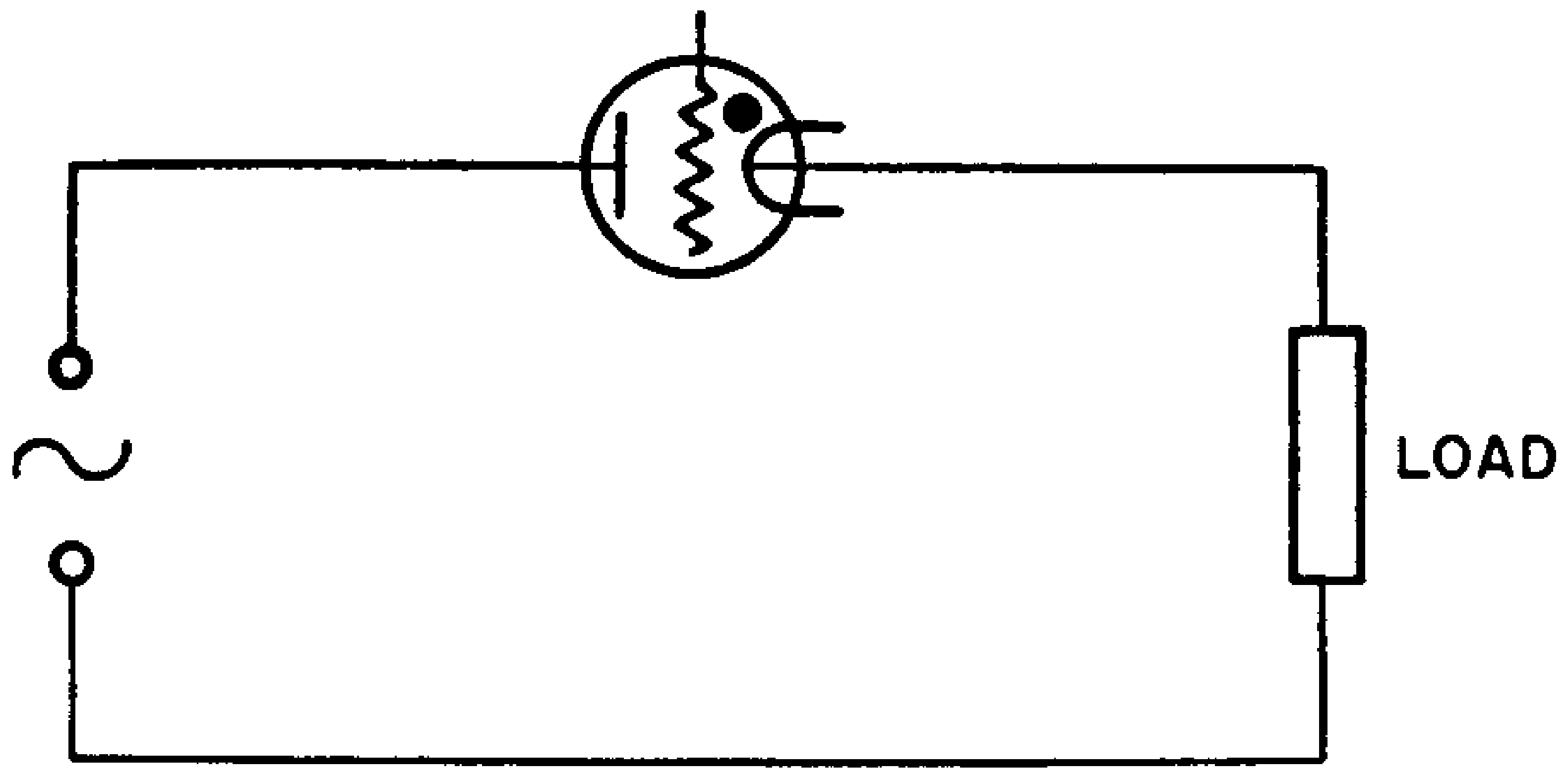


Figure 10

The simple circuit of Figure 10 may be shut off completely or turned on to give a pulsating d-c. output with an rms voltage of 71% of the a-c. supply less tube drop allowance. Due to the a-c. form factor the tube can pass an rms. current of 157% of its d-c. rating without overload. Peak forward voltage is 1.41 times a-c. line voltage plus allowances. If a transformer is used the magnetic circuit usually requires an air gap to prevent saturation by the d-c. component of primary current.

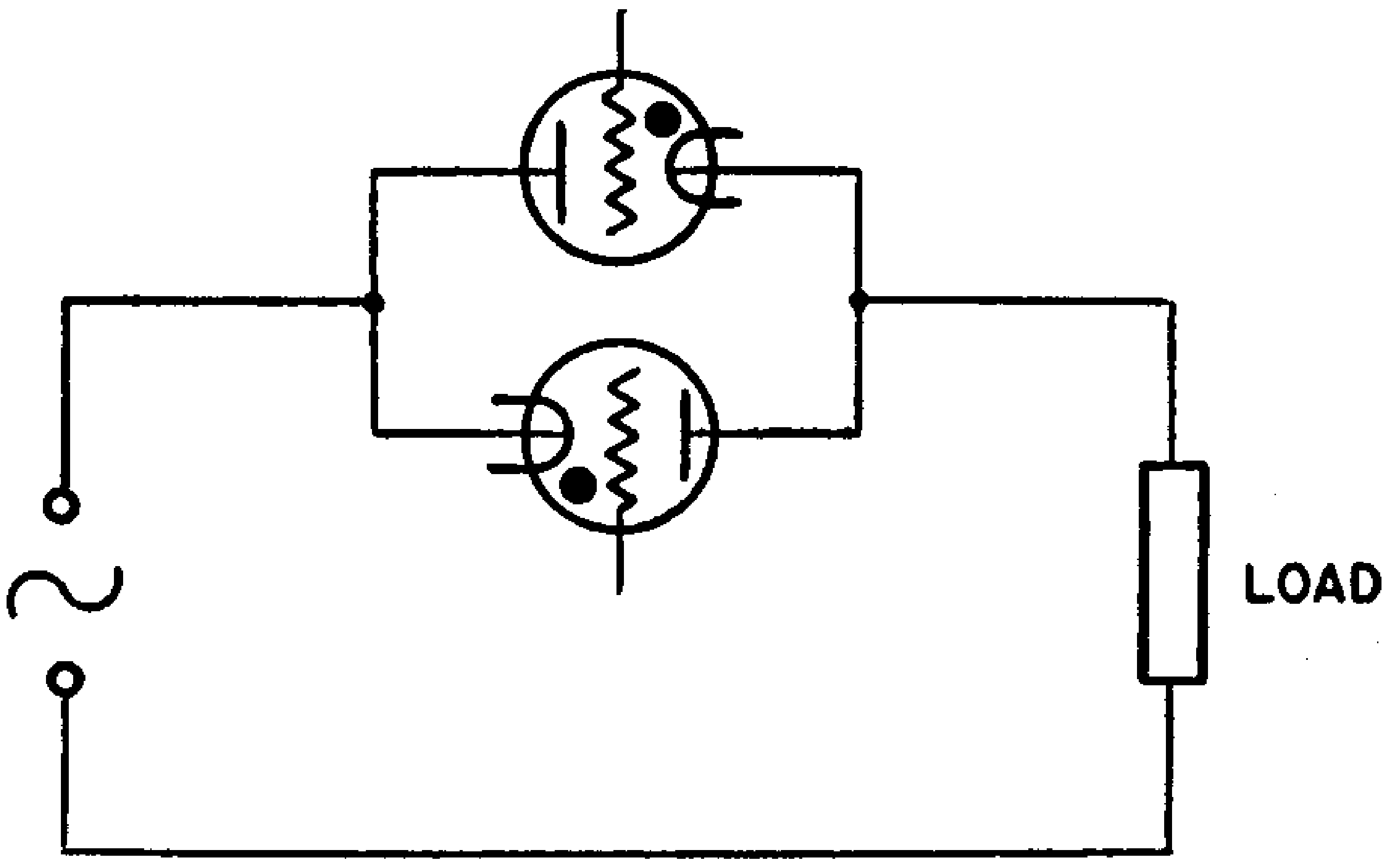


Figure 11

Figure 11 shows the so-called back to back connection. It shuts off completely, passes an a-c. output current when wide open equal to 2.22 times the average d-c. current rating of each tube and applies a peak forward voltage of 1.41 times line voltage plus allowances. The maximum a-c. output voltage is line voltage less tube drop. With an inductive or transformer load the grids should restrain firing until after current zero, otherwise any slight unbalance has a cumulative saturating effect which builds up to a d-c. short circuit on one tube limited only by the d-c. resistance of the load.

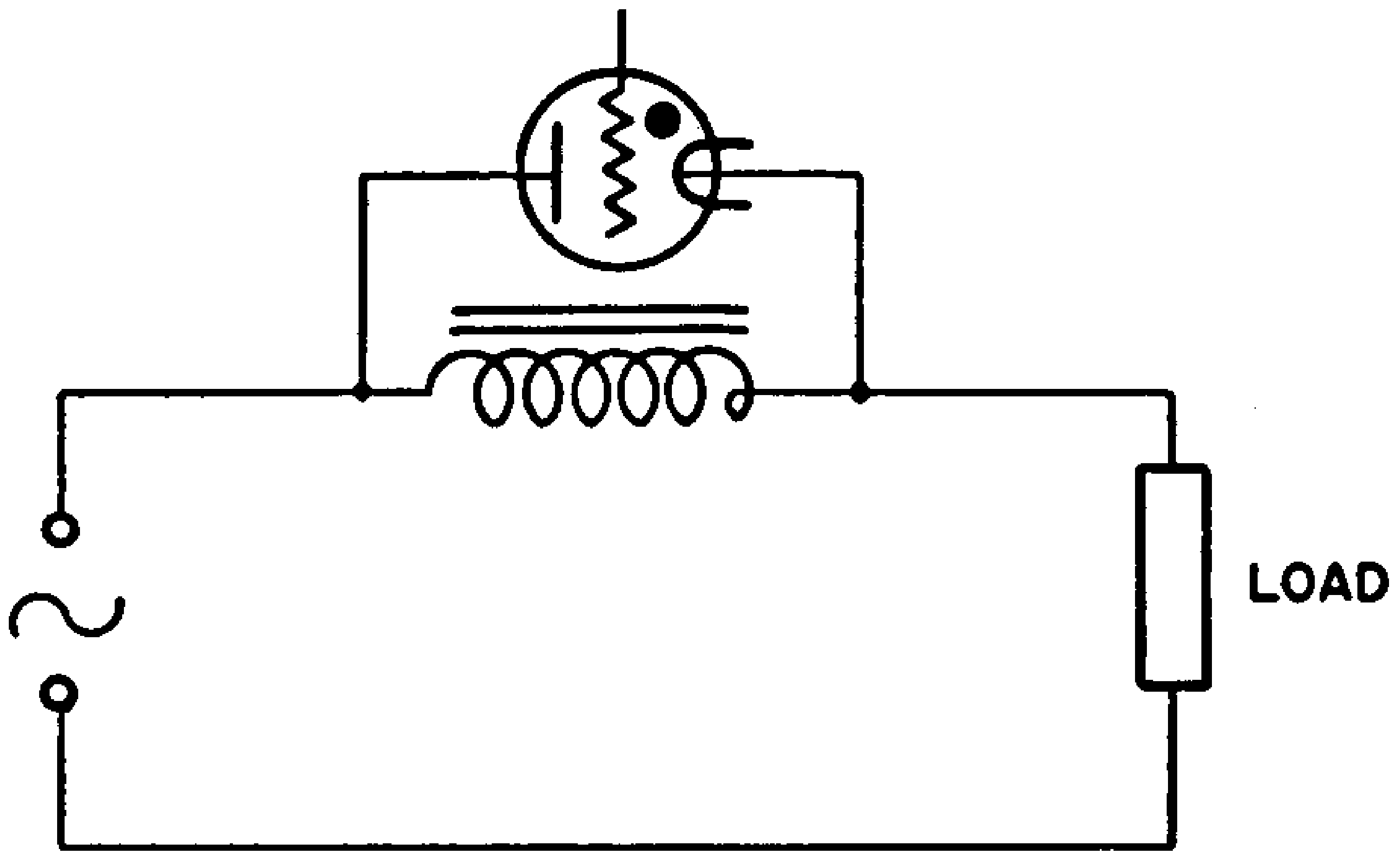


Figure 12

The circuit of Figure 12 utilizes the saturating effect of the d-c. component of current through the choke for control purposes. This circuit does not shut off completely as there is always a small inductive magnetizing current flowing. There may be a time delay of the general order of one cycle in initiating current flow. The inductor design affects the circuit but to a first approximation rms load current may approach twice the d-c. tube current if the tube is full on. Output voltage is roughly line voltage less tube drop and peak forward voltage is 1.41 times line voltage plus allowances.

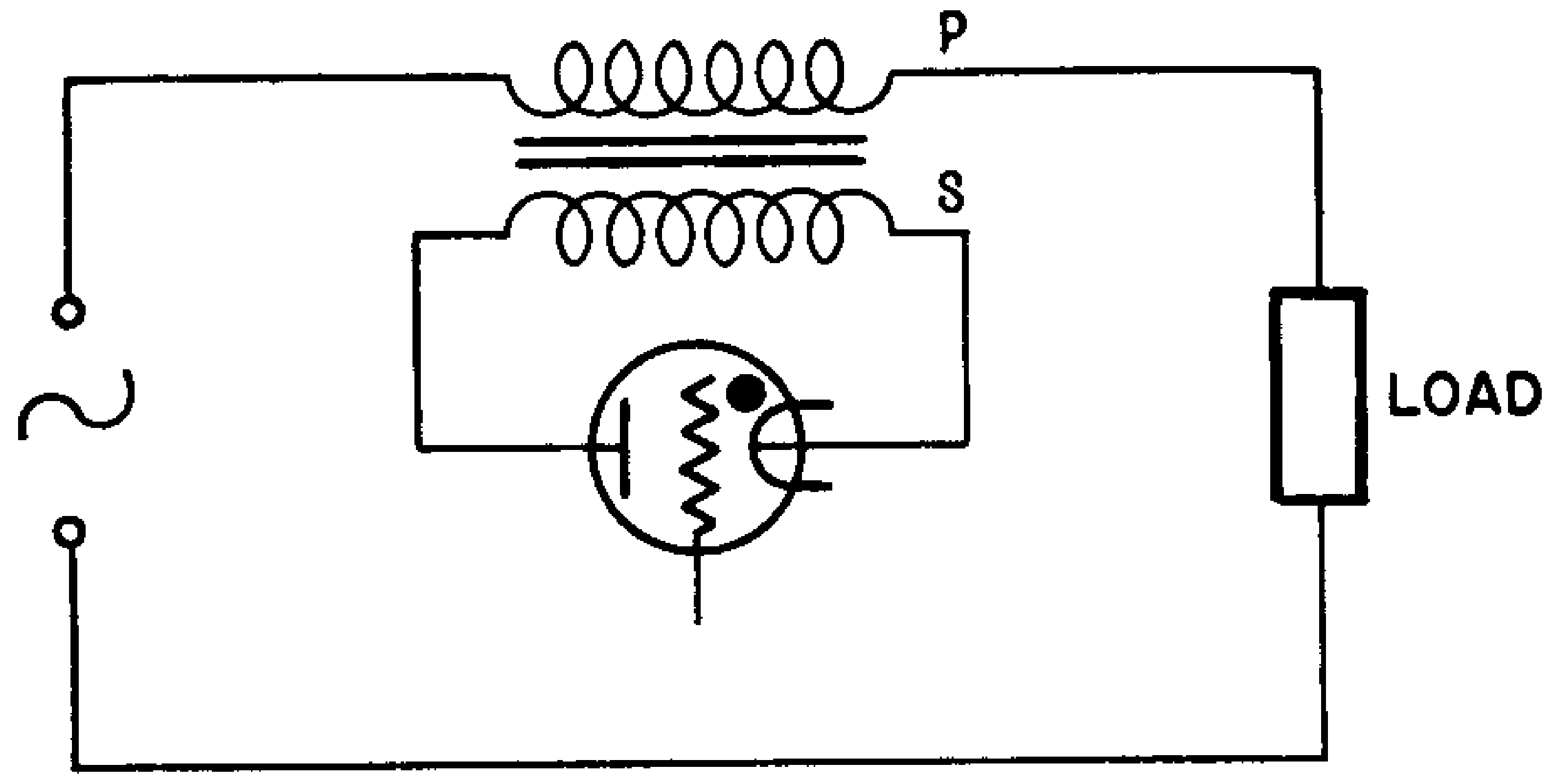


Figure 13

Figure 13 allows the use of the most efficient voltage for the tube regardless of line voltage. For this circuit tube voltage factors for Figure 12 should be divided by N (the ratio of primary to secondary turns). The tube current is in the order of 0.9N. or less, times the a-c. line current when the tube is fired full on.

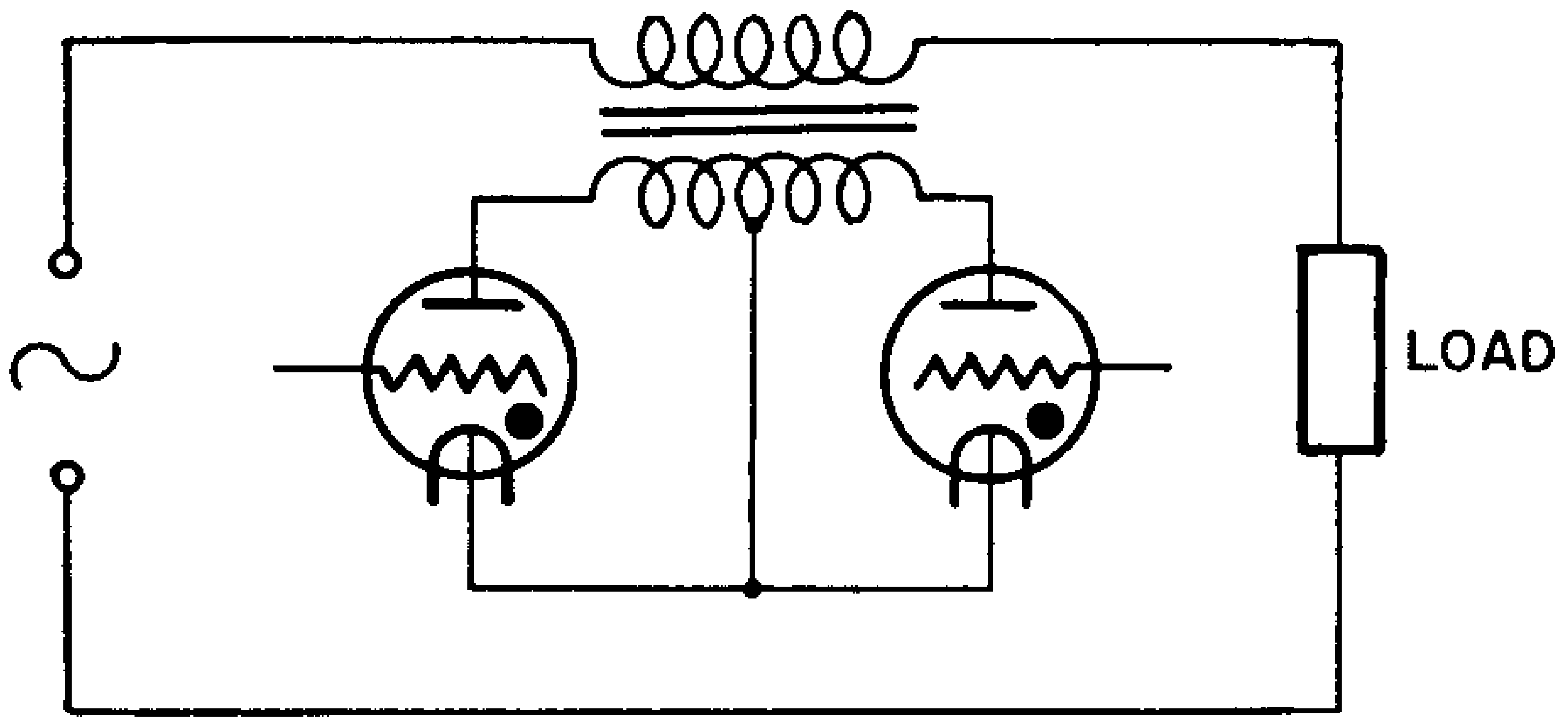


Figure 14

The circuit of Figure 14 passes a small magnetizing current at all times but does respond within one half cycle to grid control voltage. The maximum a-c. output voltage depends on transformer characteristics. The tube average d-c. current is 0.45N times the a-c. line current for maximum conduction where N is the primary to ½ secondary turn ratio. Peak forward voltage is 1.41 E plus allowances where E is the maximum a-c. voltage across ½ the secondary when the tubes are not conducting.

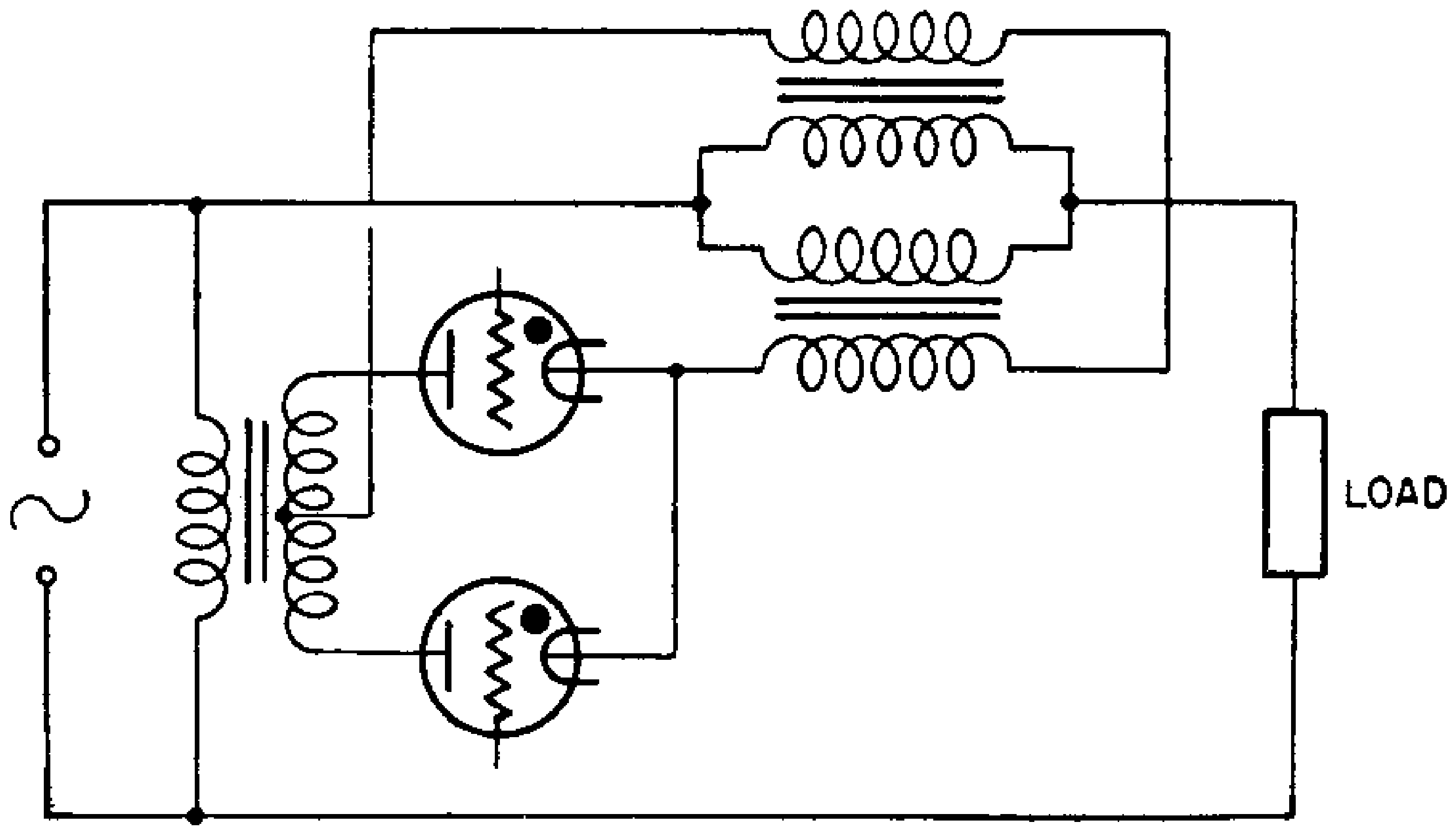


Figure 15

Figure 15 takes advantage of magnetic amplification to increase the KVA controlled with given tubes at the expense of speed of response. Amplification of the controllable power output of the tubes may be obtained, the amount depending largely on the allowable current when both tubes are shut off, and on the acceptable physical size of the reactor. Speed of response of the particular saturating reactor sets the d-c. supply requirements of the controlled rectifier.

(3) MOTOR LOADS[11]

Any of the circuits in Table I may be used to supply variable d-c. voltage to a shunt, series, or compound wound d-c. motor. For loads heavy enough to insure continuous conduction by reason of motor inductance, the calculations for inductive loads apply. At lighter loads and with a half wave circuit the motor back emf in the shunt and compound motor cases behaves like a very large capacitance. The difference between the instantaneous line voltages and the back emf of the motor is absorbed in the motor inductance in which case the flux through the inductance fluctuates. In such circuits, laminated pole pieces reduce eddy current losses due to this flux.

Figures 16, 17, 18, 19, show some of the many common ways of controlling reversing motors.

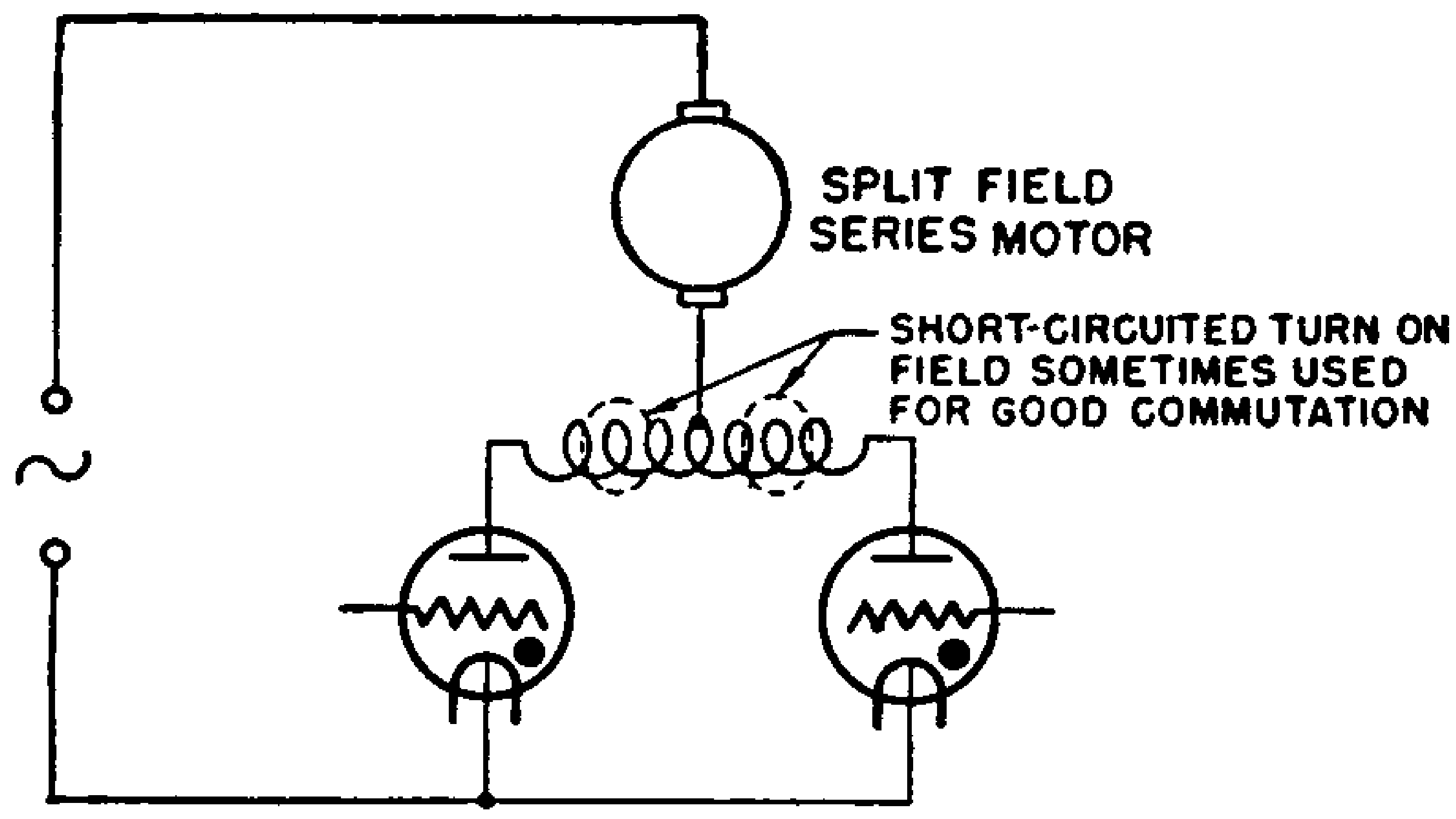


Figure 16

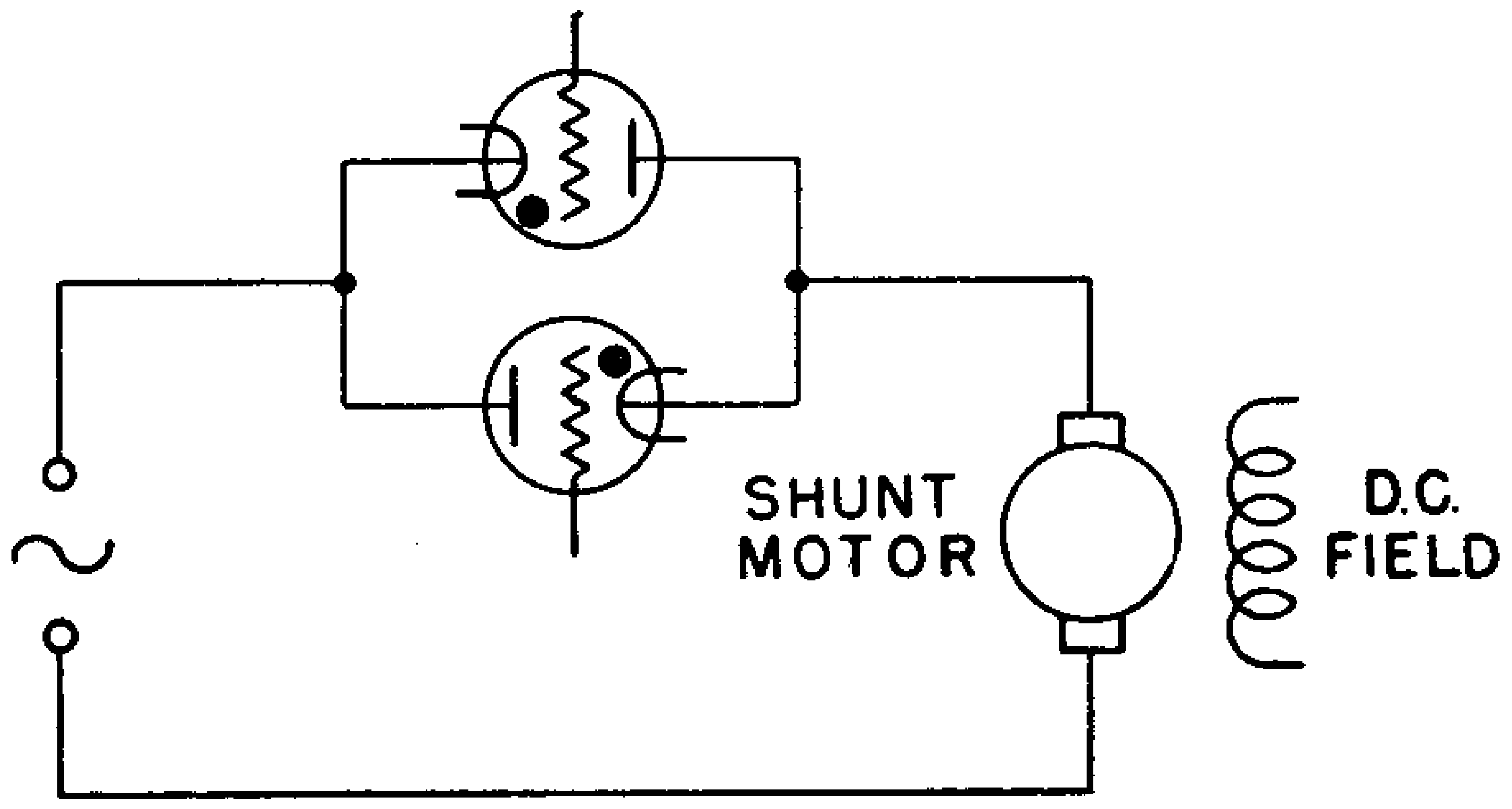


Figure 17

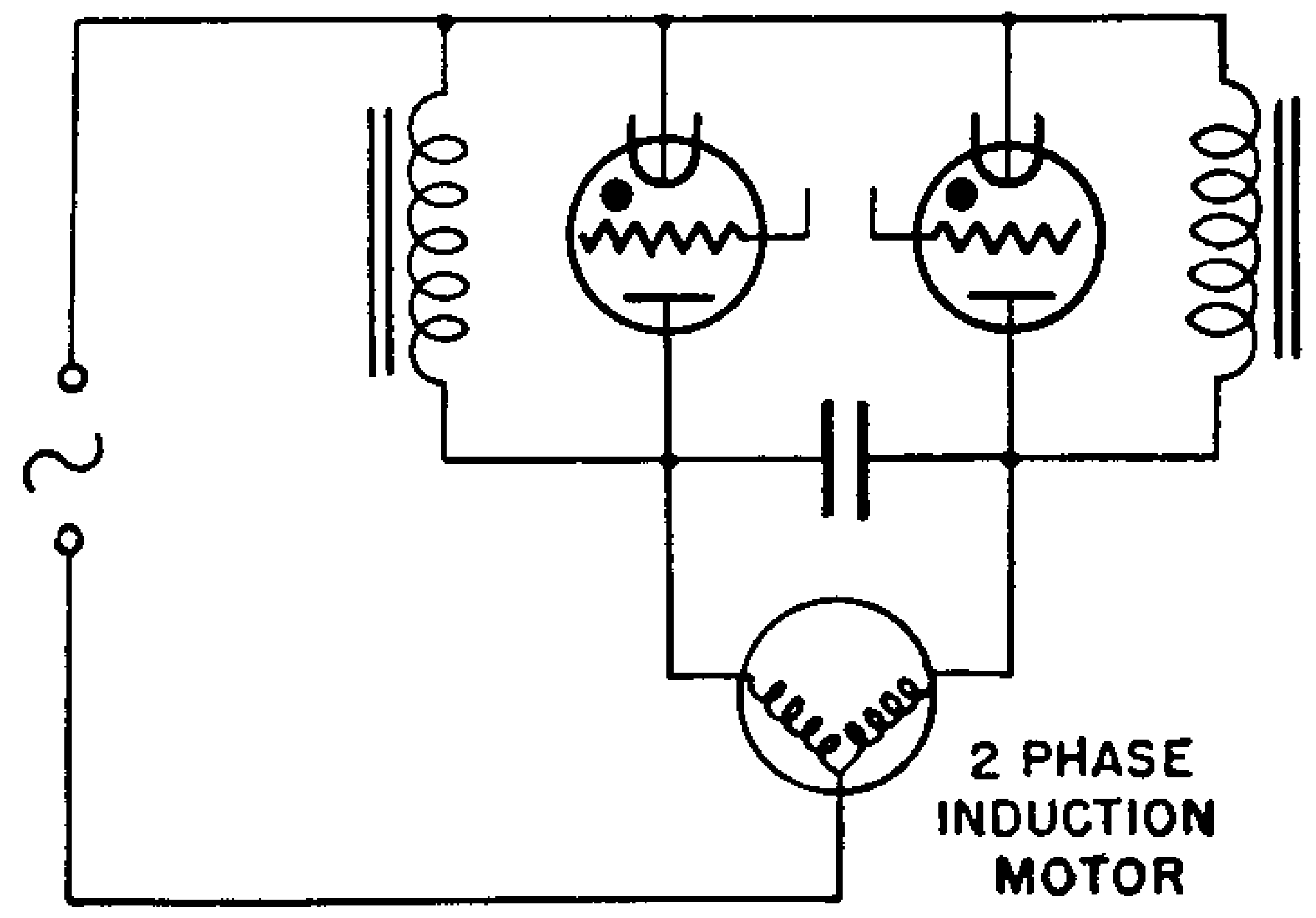


Figure 18

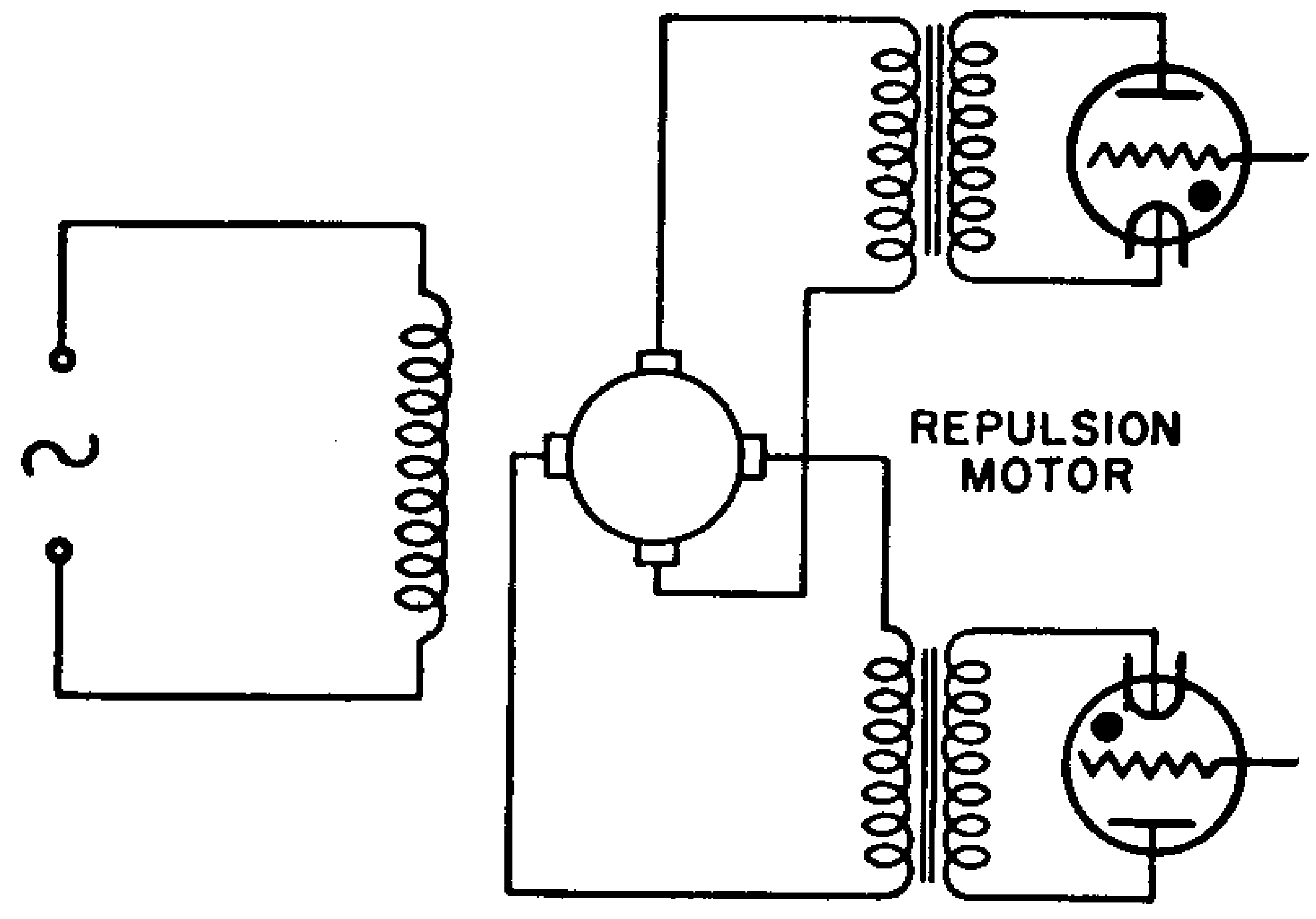


Figure 19

(4) INVERTERS[6]

If the d-c. side of a full wave rectifier contains a source of d-c. power, and if there is series inductance in the d-c. circuit it was shown on Page 19 that power is converted from d-c. to a-c. and returned to the a-c. supply when the grids are fired at delay angles greater than 90°. If the firing angle approaches 180°, the anode of the conducting tube is negative too short a time for the grid to regain control by deionization, and the inverter will misfire. For a firing angle of 150° the oscillograms appear as follows for the single phase case.

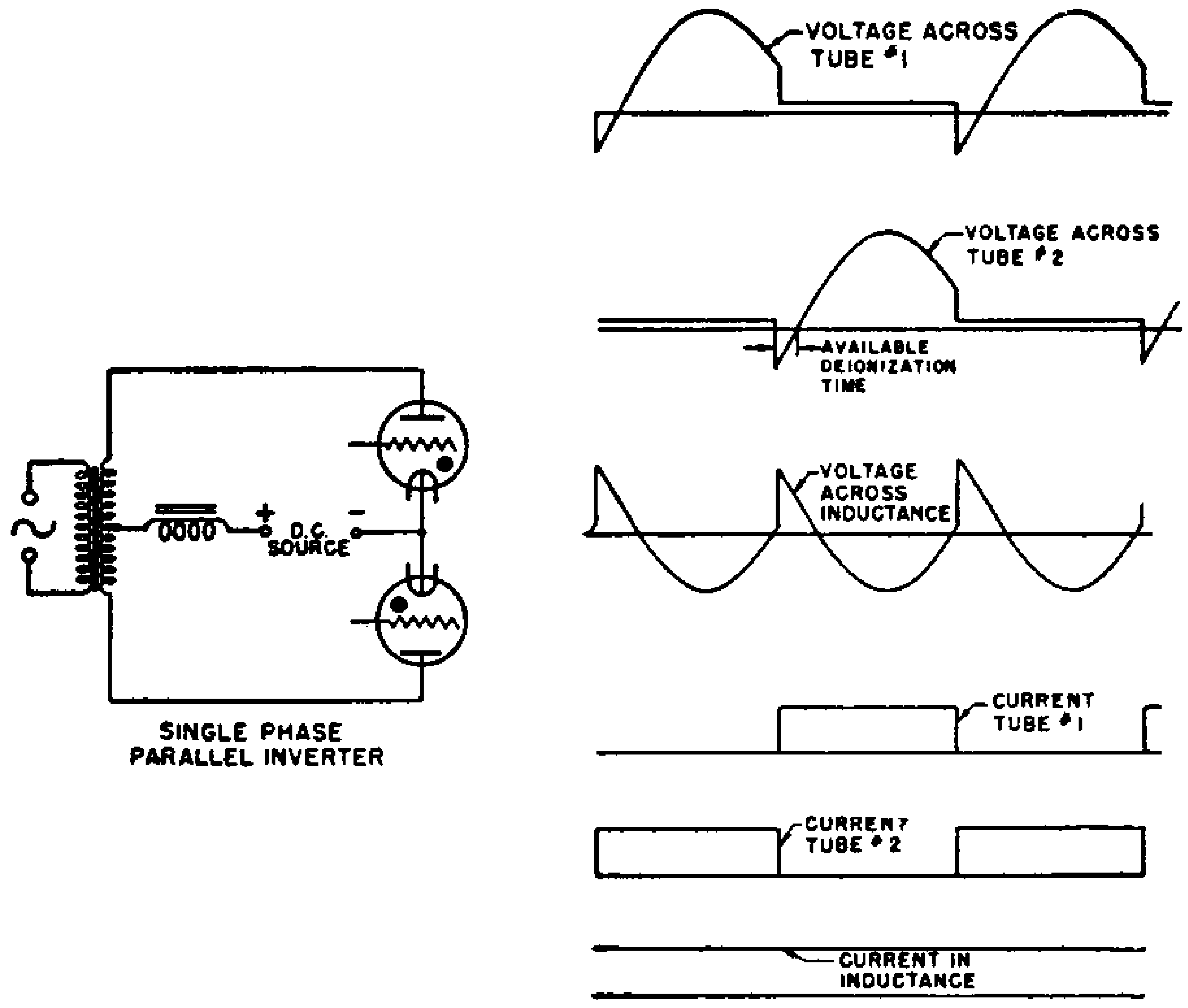


Figure 20

If the transformer has no losses, and small leakage reactance, a-c. current is N times the d-c. current regardless of firing angle where N equals the turns on one half of secondary divided by turns on the primary. If ideal transformers are assumed the a-c. voltage is Edc/cos y where y is the delay angle and Edc is the available d-c. input voltage, less tube and circuit resistance drop. Since the actual effective d-c. volts consumed by overlap is independent of firing angle the correction for overlap follows the reasoning given for this effect under rectifiers.

If instead of connecting the a-c. primary to a power system it is connected to an independent load, two methods of operation are available. In one, the frequency of the grid drive voltage may be set by an independent oscillator. In this case the load must contain enough capacitance or its equivalent, to make the net power factor leading at least enough to allow deionization. Any change in net load power factor will vary y and the ratio of a-c. to d-c. voltage. Thus, output voltage may be regulated by either changing the d-c. input voltage as the load power factor shifts, or adjusting the power factor to give the desired output voltage, provided always it is kept sufficiently leading to insure deionization.

Another method of operation of an independent inverter is to use a self-excited grid circuit which maintains constant firing angle. In this case the frequency adjusts itself to whatever is necessary to make the particular load give the set power factor angle. Since firing angle is constant the a-c. to d-c. voltage ratio remains constant except for the inverter IR drop.

In general the higher the ratio of wattless to watt energy in the load of an independent inverter, the better the wave form. The series inductance is usually large enough to insure continuous d-c. current. If it is made too large the a-c. voltage builds up to a very small anode voltage on the first cycle after d-c. voltage is applied and large grid drive is required to insure starting.

There will be an abrupt change of characteristics at light loads if the inverter shifts its operation from the continuous current region to the discontinuous one. In the latter, the inverter may be considered as two relaxation oscillators alternately carrying the load.

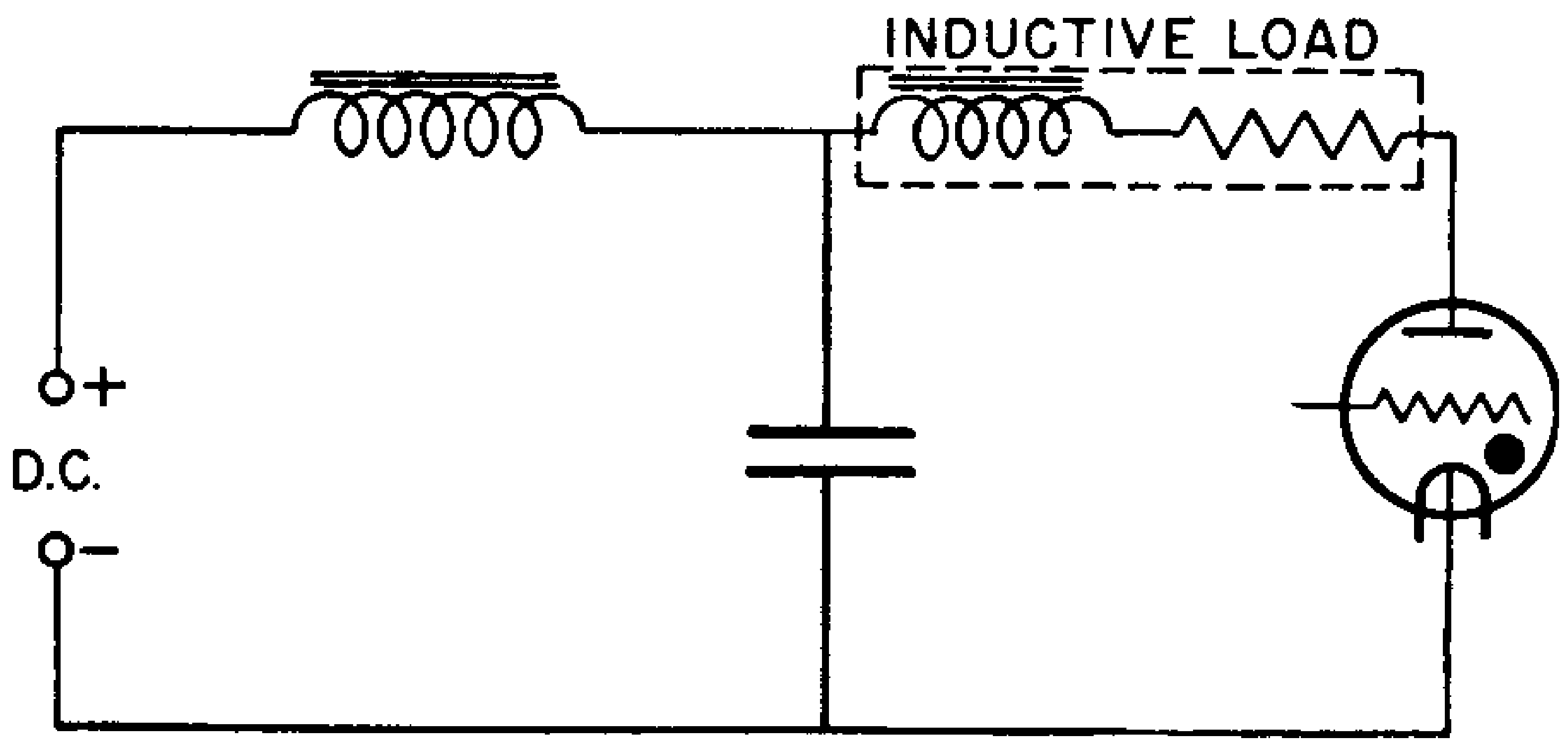


Figure 21

A single relaxation oscillator is often used to give pulses of high current as, for example, to magnet loads as shown in Fig. 21.

The inductance of the load causes capacitor current to flow through the tube until the capacitor is recharged with opposite polarity. This allows time for the tube to deionize before the anode voltage becomes positive again. The following oscillograms are obtained.

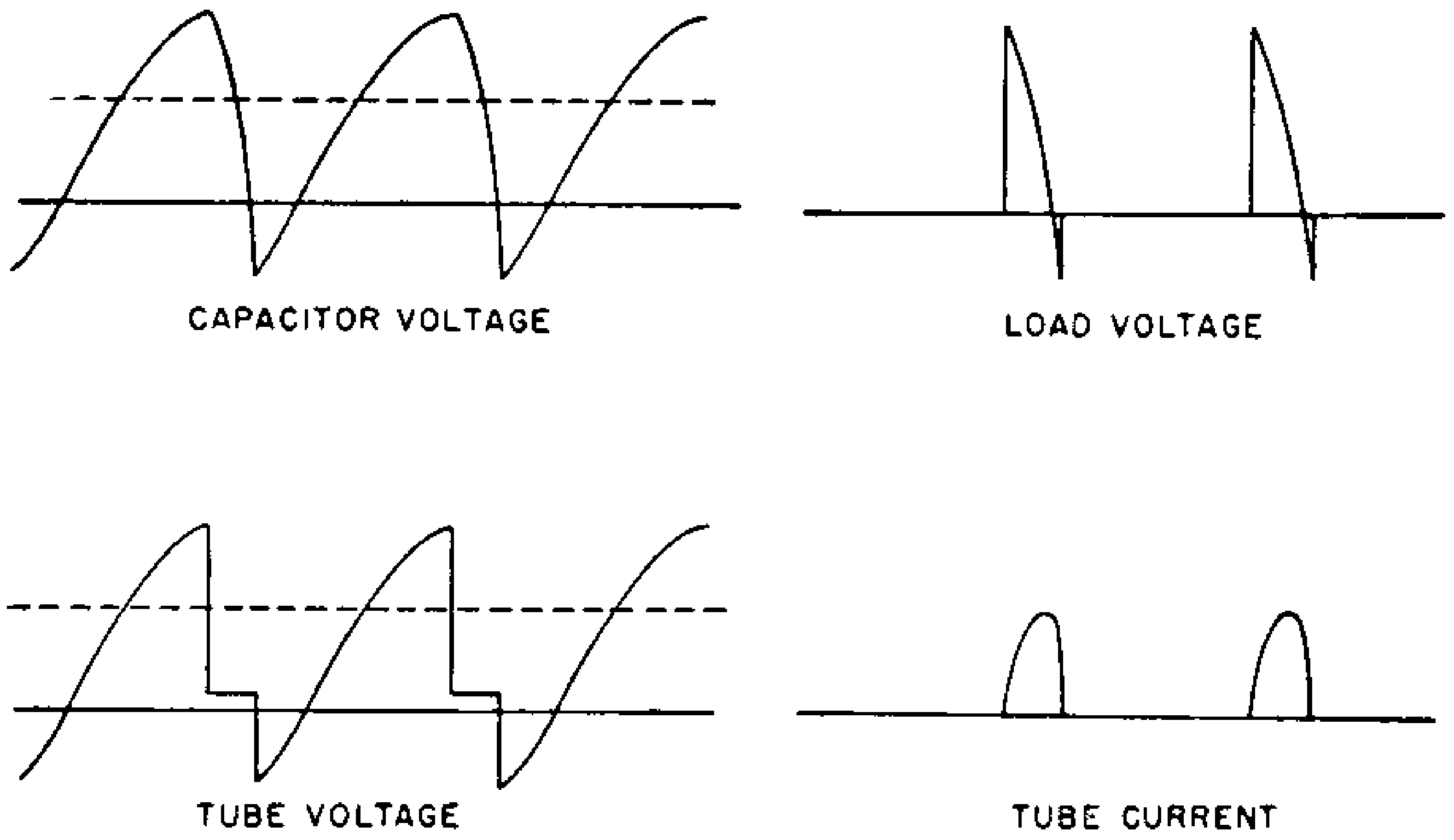


Figure 22

(5) COMMUTATION FACTOR REQUIREMENTS OF POWER CIRCUIT

Operation of a gas filled tube at higher than its rated commutation factor* quickly causes failure. It is therefore necessary to know the commutation duty imposed by the circuit and to modify it if necessary to meet the tube rating.

Many circuits apply inverse voltage at the sine wave rate of increasing voltage after each conduction period. This duty is so light it may be ignored. This group of circuits includes rectifiers without firing delay, grid control rectifiers operating in the discontinuous current region with loads that are effectively resistive, and control rectifiers with back rectifiers (but not the back rectifiers themselves).

There is another group of circuits in which tube current gradually builds up and dies down during the conduction period, after which initial inverse voltage may be suddenly applied. In this group the damage done is usually insignificant but occasionally average life may be raised from something in the order of 10,000 to 20,000 hours by the addition of a small capaci-

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*See page 15 for definition, and page 31.

tor and resistor connected across the tubes, or "cushion circuit" as this combination is called. This group includes circuits such as rectifiers supplying motors or capacitive loads running in the discontinuous region, half wave circuits, relaxation inverters, and series transformers.

There is a third group in which, on every cycle, each tube conducts full current up to the instant its successor is fired and shortly thereafter high initial inverse voltage is applied to the anode. This may be damaging and requires study. The group includes full wave or polyphase rectifier or inverter circuits operating in the continuous current region with firing delayed by grid action, and half-wave tubes used as back rectifiers with firing angle of the controlled tubes retarded.

To analyze the process that occurs during the few microseconds necessary to commutate, an example may be taken. A full wave controlled rectifier with firing delayed by grid action and load inductance so great that the ripple current is small, is a typical case. The inherent leakage inductance of each secondary winding of the transformer is indicated at L_1, L_2. Cushion resistors and capacitors C_1, C_2 to limit voltage recovery are shown.

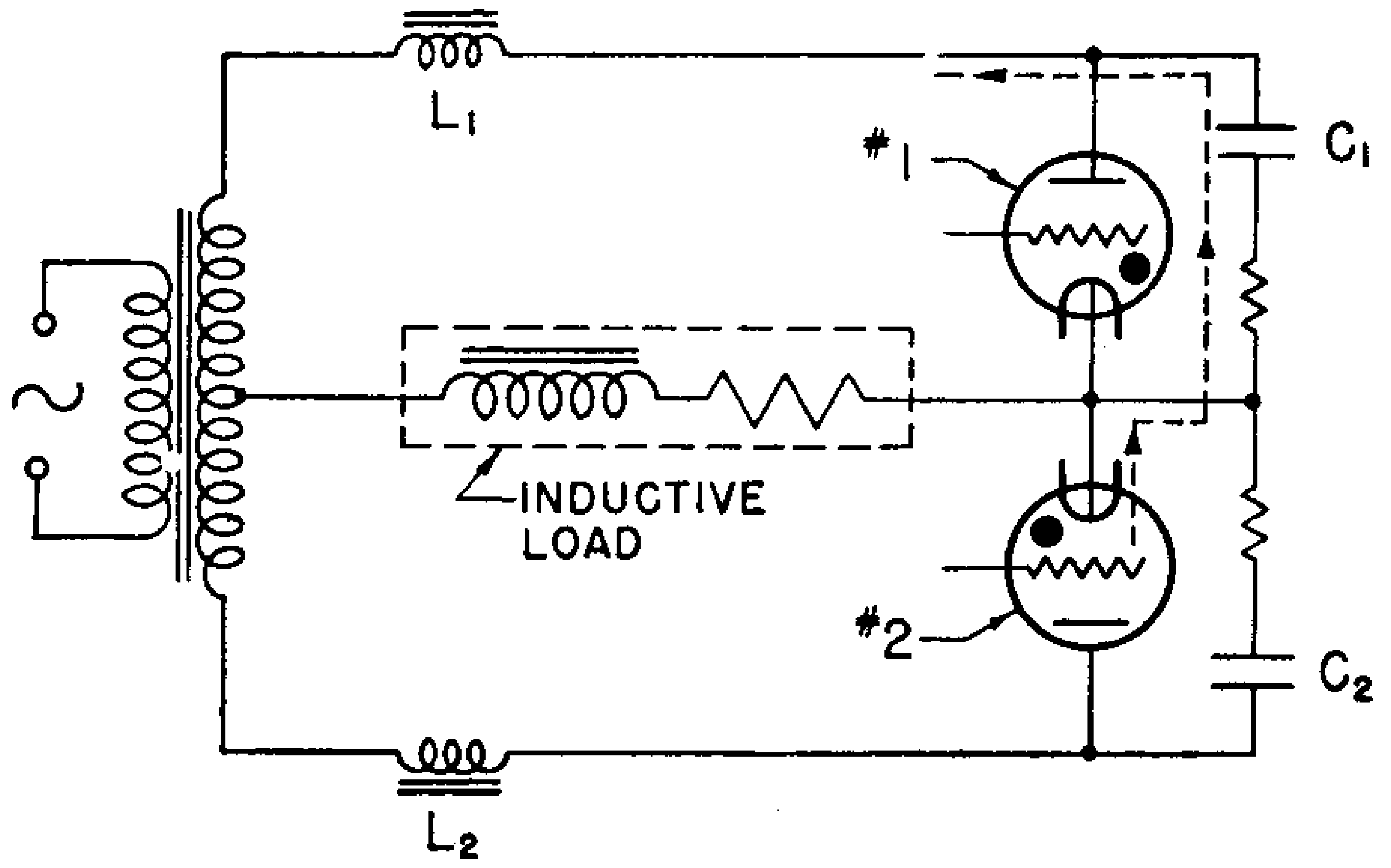
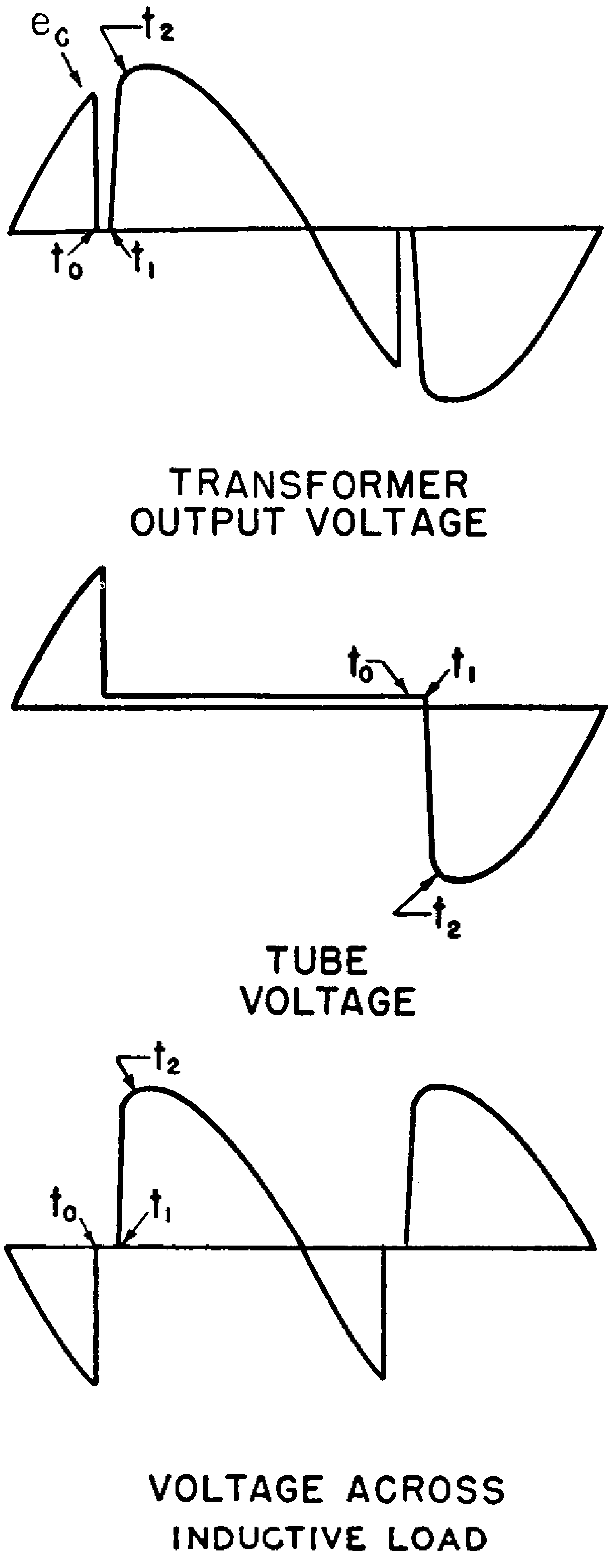


Figure 23

In this circuit the load inductance forces current to flow through the conducting tube (assumed #1 above) beyond the end of each positive half cycle by generating a voltage to more than oppose the voltage of the transformer secondary as it goes negative. This conduction continues until the grid circuit allows the next or "entering tube" (#2 above) to fire.

The events of present interest follow the firing of this entering tube: they are depicted in the following oscillograms. First, since both cathodes are tied together and both tubes are conducting and have substantially equal arc drop, their anodes are at the same potential. Hence the transformer voltage is effectively applied to the leakage inductance, and the net transformer output voltage is zero. The transformer voltages cause a rise of current in L_2 and a decay of current in L_1 at an initial rate of ec/ $(L_1 + L_2)$ where ec is the instantaneous commutating (anode-to-anode) voltage. The load inductance holds the sum of these two currents constant. These conditions hold for a period called the current commutation



TRANSFORMER OUTPUT VOLTAGE

TUBE VOLTAGE

VOLTAGE ACROSS INDUCTIVE LOAD

Figure 24

time Tc, indicated on the oscillograms from t_0 to t_1. (This time has been exaggerated to show in the figures.) During this short period current has been dying out through tube #1 (tube leaving conduction) at a substantially constant rate.

As the current through the leaving tube reaches zero, conduction ceases. It is prevented from growing in the reverse direction by the rectifying action of the tube. Full load current now flows through the entering tube and current commutation is complete. Were it not for the capacitances in the circuit the voltages absorbed by the leakage inductances would at this instant disappear (since there is no longer a rate of change of current through them). However, capacitance is present and hence a period of voltage recovery ensues, indicated from t_1 to t_2. For voltage to appear across the leaving tube current must be built up through L_1 and L_2 creating an IR drop in the damping resistor and a charge in the capacitor. The path of this current is shown in the figure by the dotted arrows. The function of the resistor is to damp the circuit so that it will not oscillate and overcharge the capacitor.

Since the tube has a limited permissible product of current decay rate times voltage recovery rate, a circuit which is found to exceed the tube's rating may be corrected by either increasing the transformer leakage inductance (This affects both current and voltage rates. In the case of a parallel inverter,

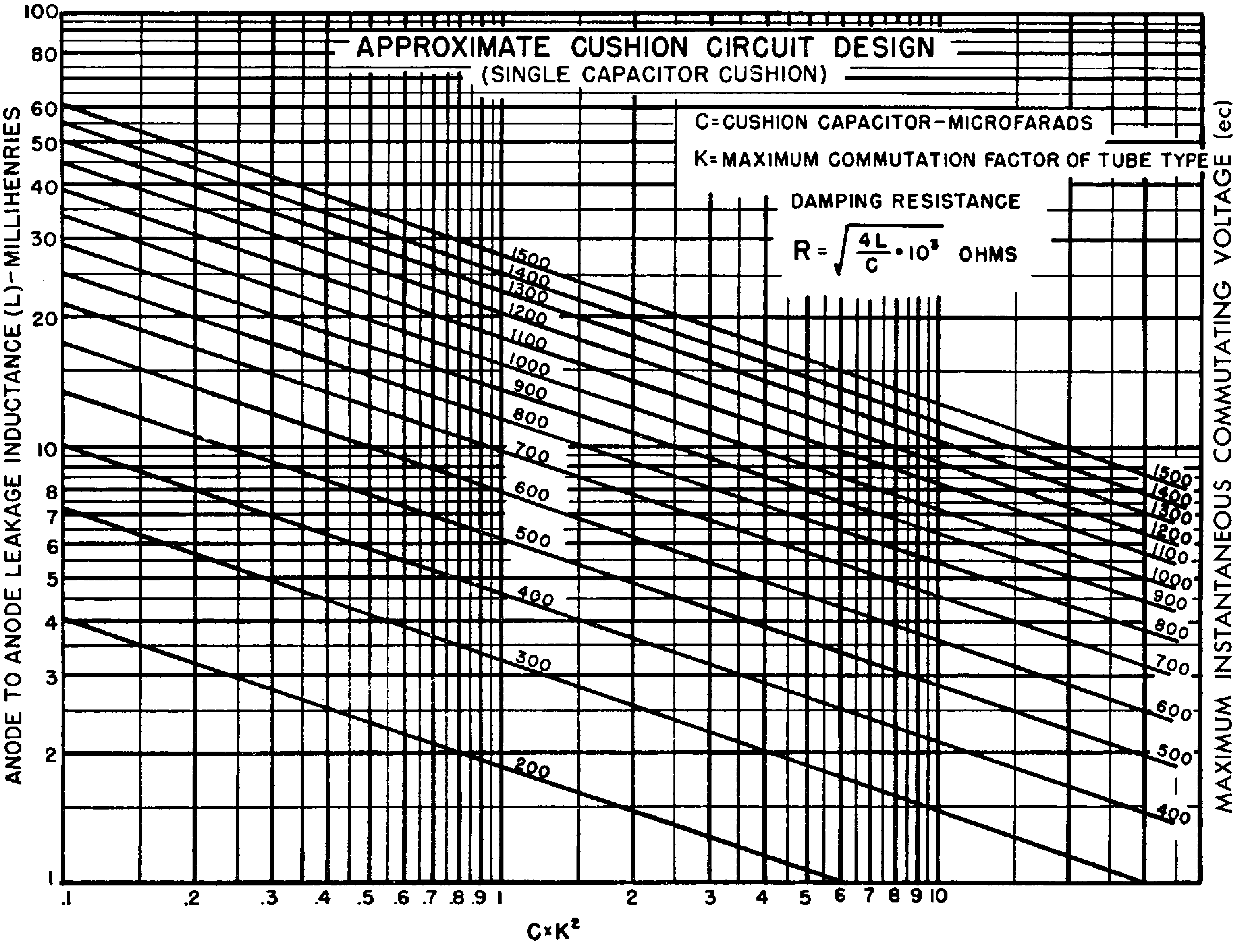


Figure 25

a small inductor may be connected in series with the commutating capacitor), or by adding a larger cushion capacitor, with the consequent lower damping resistor. Distributed capacitance of the windings and hysteresis and eddy current losses in the various inductances make it preferable to measure the various rates with an oscilloscope rather than attempt to compute them. This measurement is described later under laboratory techniques. The usual procedure is to try one size of capacitor, adjust the resistor until there is no overshoot, then measure the rates. If above the tube rating, larger capacitors are tried and the process repeated. As a preliminary estimate, Fig. 25 may be used if the anode-to-anode effective leakage inductance is known.

Computation of the power loss is complex. However, for a single phase full wave circuit it is always less than

$8E^2fC\ (1+\pi^2 fCR)$ watts per side, where

E = rms volts anode to center tap
f = frequency
R = cushion resistor in ohms
C = cushion capacitor in farads.

If the commutating inductance is very low, or the operating frequency is high, a substantial reduction of commutation duty over a simple cushion circuit, for a given power loss, may be obtained by using a second capacitor, connected across the first capacitor and most of the cushion circuit resistor. Such an arrangement reduces greatly the rate of rise of initial inverse voltage especially over the first part of the transient. Some series resistance in the cushion circuit is needed to hold the peak tube current within tube rating.

Grid Circuits

(1) TYPICAL METHODS OF GRID CONTROL

The basic problem in grid circuit design is to (1) convert some quantity to be controlled into a voltage, (2) operate on the voltage to cause it to shift the firing point of the tubes in the proper manner and maintain this firing point despite disturbing factors[12] which may be classed generally as noise, such as line transient surges, critical grid current changes and other shifts in tube characteristics, carry-over effects from the preceding cycle and disturbances incidental to the starting or stopping of conduction in some other tubes in the circuit. Discussion may conveniently be considered under these headings.

Often the thing to be controlled is available directly as a voltage, for instance, when regulating a generator or alternator. If position is to be controlled it may be converted into a voltage by using position to move a potentiometer, a synchro, a magnetic armature of an inductance, one plate of a capacitor, a strain gage, or a shutter in a light beam to a photo electric cell. Currents may be controlled by using the voltage created across a resistor in series with the circuit, by the effect of the magnetic field in a saturating reactor through the winding of which the current passes, by means of a current transformer, or by the action of a magnetic field on a tube. Temperature may be converted to voltage by using a thermocouple or a high temperature coefficient resistor in one arm of a bridge. Speed may be measured with a tachometer or by the back emf of the motor being controlled. The voltage may be d-c. or a-c. of power frequency or higher. In nearly all circuits it is common practice to balance this quantity to be controlled against a reference of such magnitude that the voltage difference between it and the signal, when applied to the grids, will be large compared to changes in tube critical grid voltage. Sometimes this is done before converting the quantity to a signal voltage, often it is more convenient to do it after, by connecting in series with the signal voltage, a reference voltage equal and opposite to the desired setting. Then any deviation from desired setting results in a large deviation in the voltage to the grids. To take an example, as in Fig. 26, a 110V d-c. generator with a 110V reference voltage bucking the output would give zero grid voltage for correct generator output, and 1.1V at the grid with 1% high generator voltage, or, if the difference is amplified 10 times a 0.1% change of generator voltage gives a 1.1 volt change at the grids.

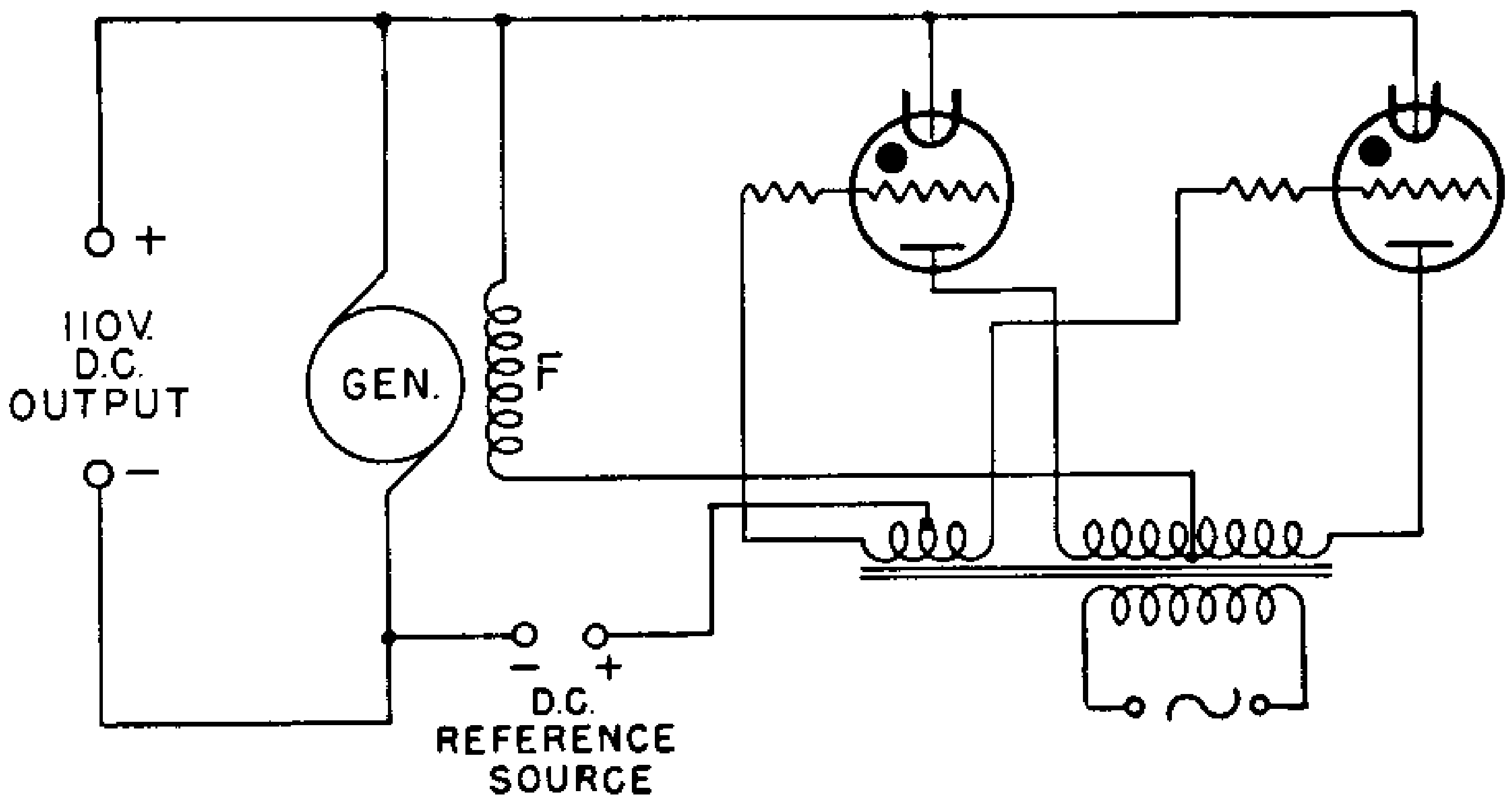


Figure 26

It might be noted that the effect on the tube firing is the same if a number of grid voltages are added in series and the sum applied through a current limiting resistance to one grid, or if a number of grids are placed in sequence across the discharge path in the tube and each voltage applied to a grid.

Having obtained a signal voltage responsive to the deviation of the controlled factor from its desired value it may be used in many ways to control the firing point of the tubes. The following summary of common techniques may be helpful.

(A) An on-off control, (i.e. most or none of any individual positive half cycle conducted with no further control until the next cycle) may be accomplished by applying a d-c., a-c., or peaked signal voltage of varying magnitude to the grids. In all but the last case there is usually a small intermediate range of signal voltage that results in some reduction in the part of each cycle passed but never less than ½.

(B) For smooth, proportional conduction control from zero to maximum each cycle any one of the following typical circuits may be used to convert the varying signal voltage. These are shown for simplicity as half wave circuits but may be full wave or polyphase if desired. Circuit component values shown are typical for 60 cps.

(a) Adding a variable magnitude in-phase a-c. signal voltage to a small fixed a-c. bias voltage which lags the anode voltage approximately 160°. (Fig. 27)

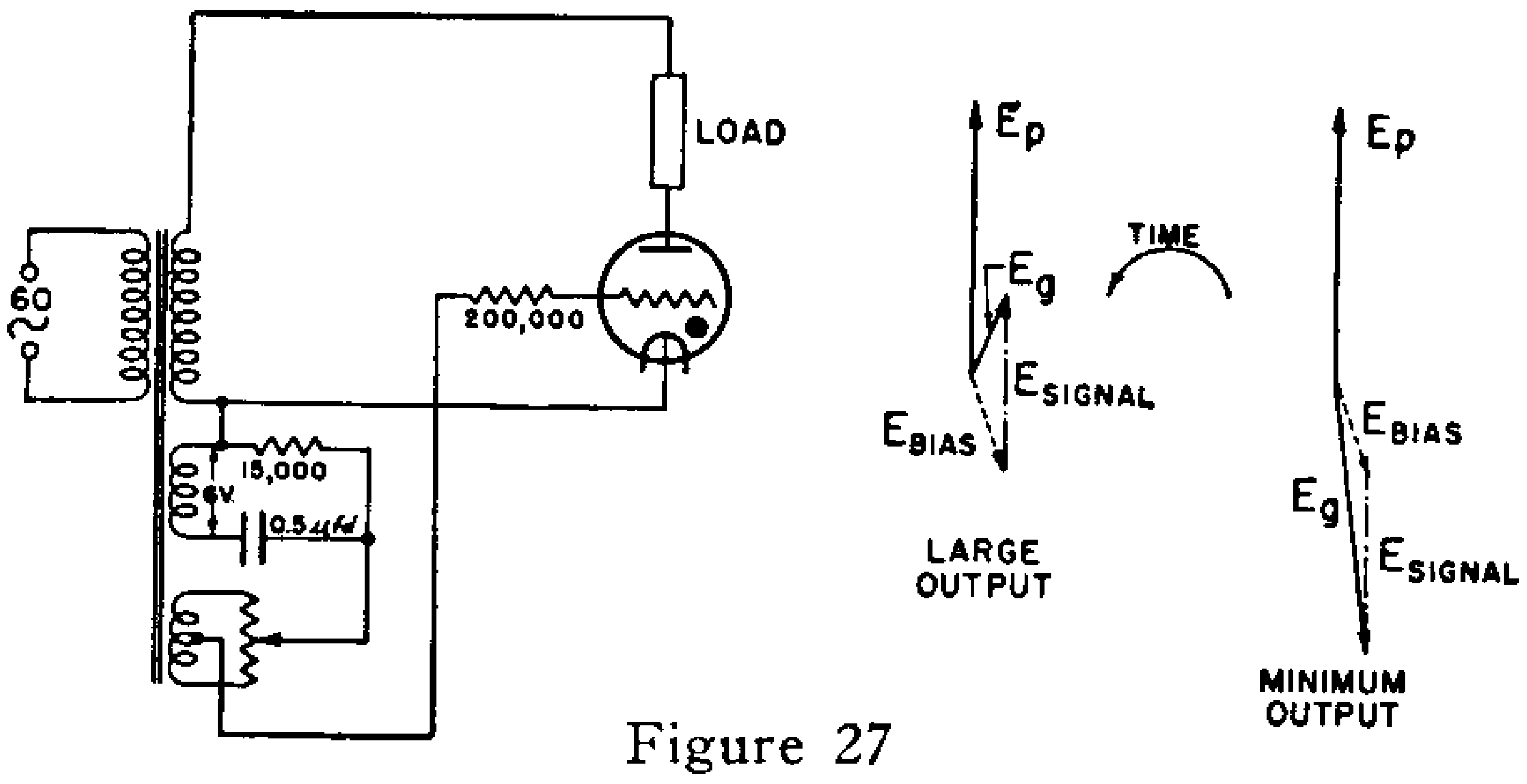


Figure 27

(b) Adding a variable polarity and magnitude d-c. grid voltage to a fixed a-c. bias voltage ("rider") which lags the anode voltage approximately 90° (Fig. 28). Normally voltages of less than 5 volts for the a-c. bias should be avoided.

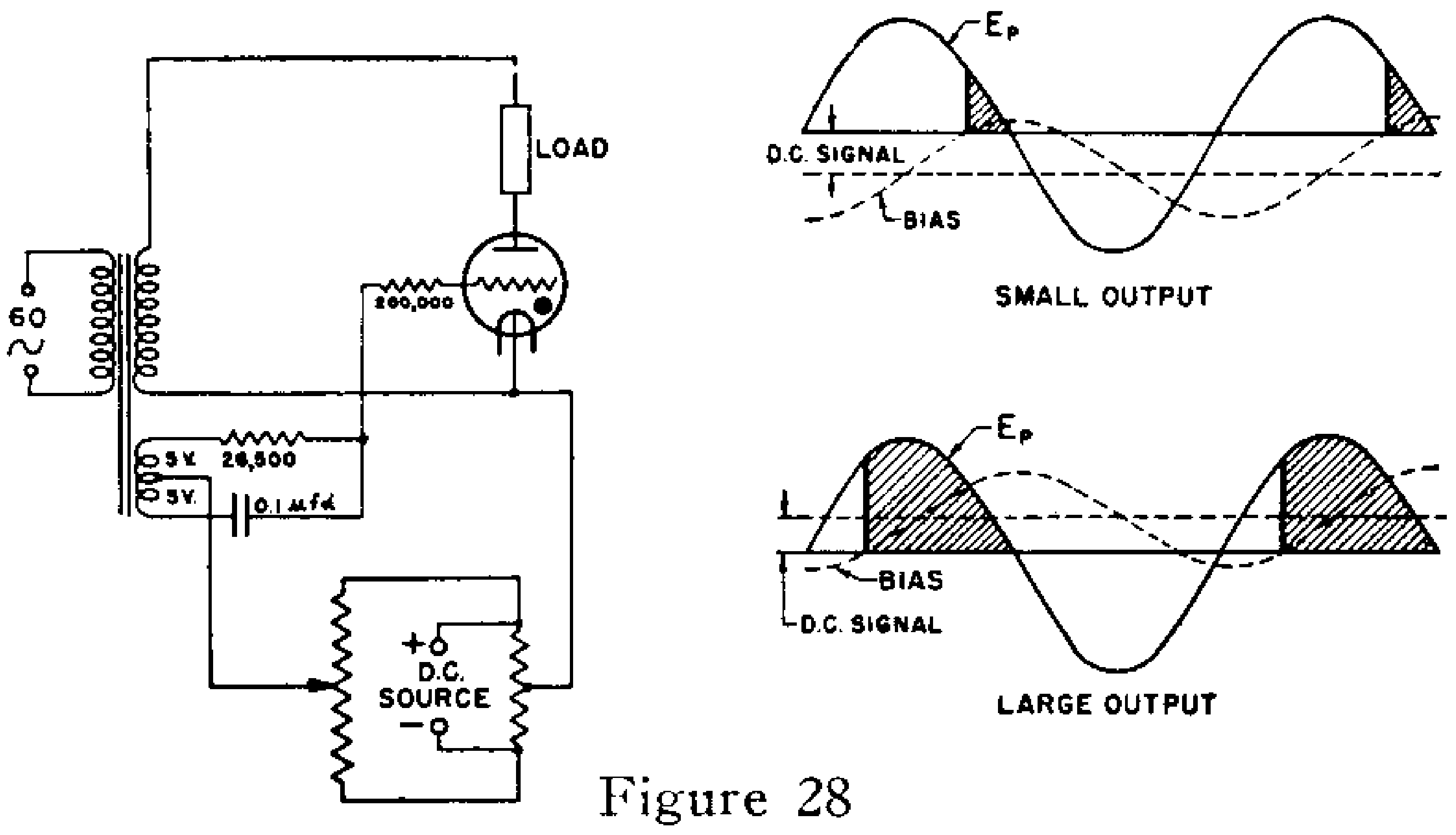


Figure 28

It is of interest to note that for the special case of a single phase full wave rectifier supplying inductive load, an in-phase rider rather than a 90° lagging rider is permissible since nearly the full range of control is obtained between 0° and 90° of grid retard.

(c) Shifting the phase of an a-c. grid voltage. (Fig. 29)

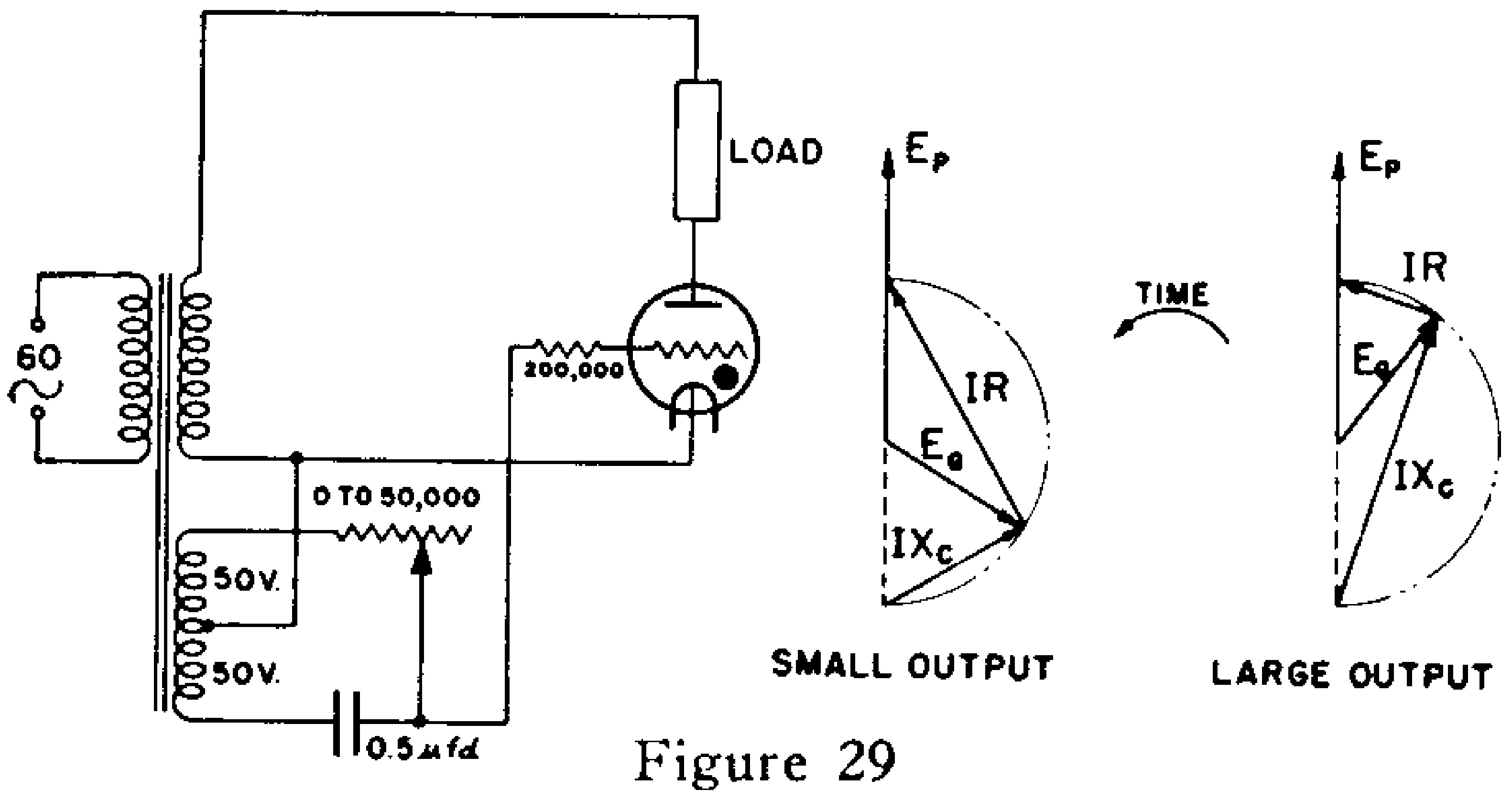


Figure 29

(d) Changing the discharge time of a capacitor or inductor which is recharged each inverse cycle. (Fig. 30)

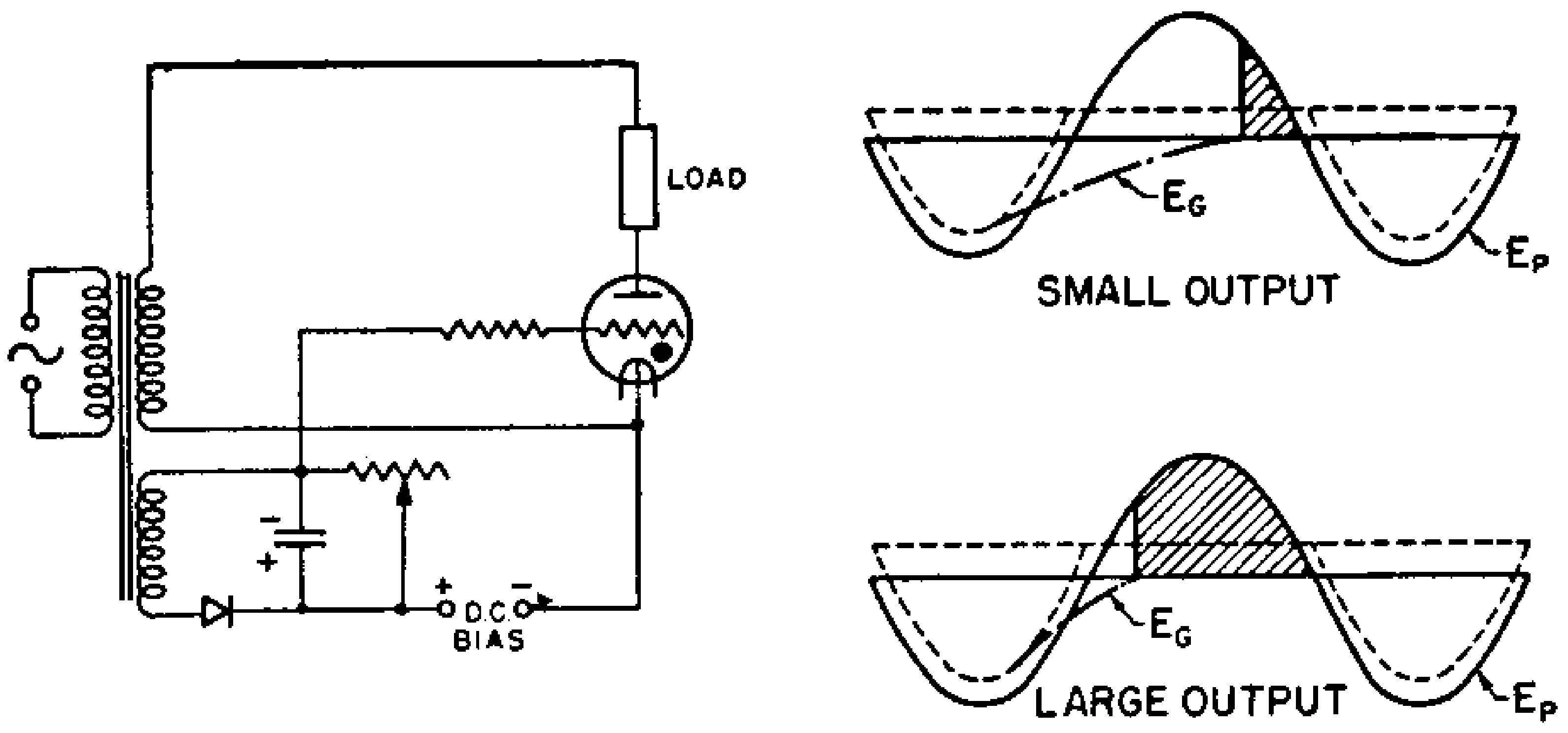


Figure 30

(e) Shifting the position in the cycle of a peaked wave. (Fig. 31)

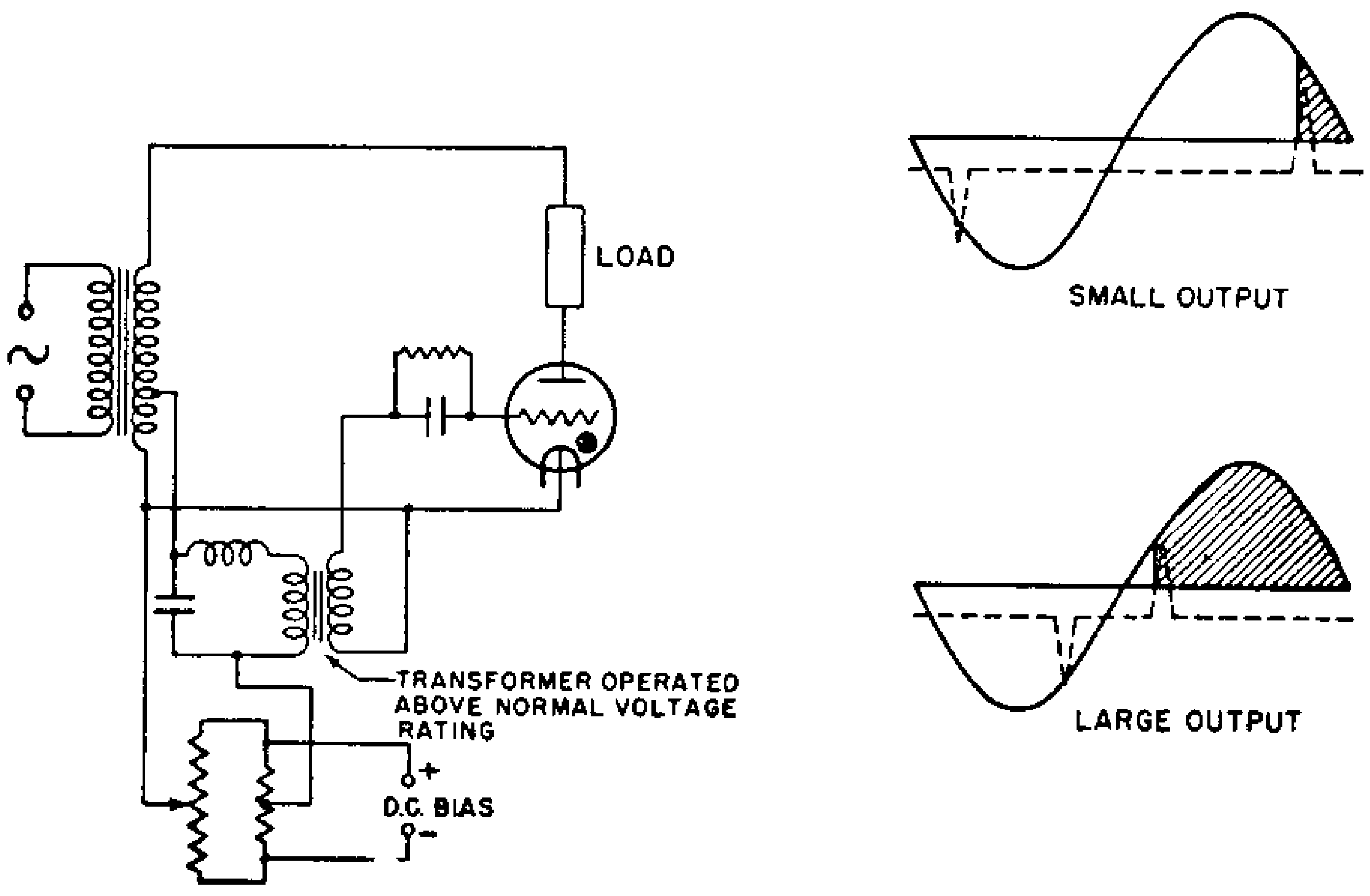


Figure 31

The small capacitor in the grid lead acts to generate a fixed d-c. bias by grid rectification. The functioning of the saturating transformer (a transformer fed from a voltage source higher than its normal voltage rating) through a series reactance (or resistance) is best understood by considering the primary current and flux shown in Fig. 32.

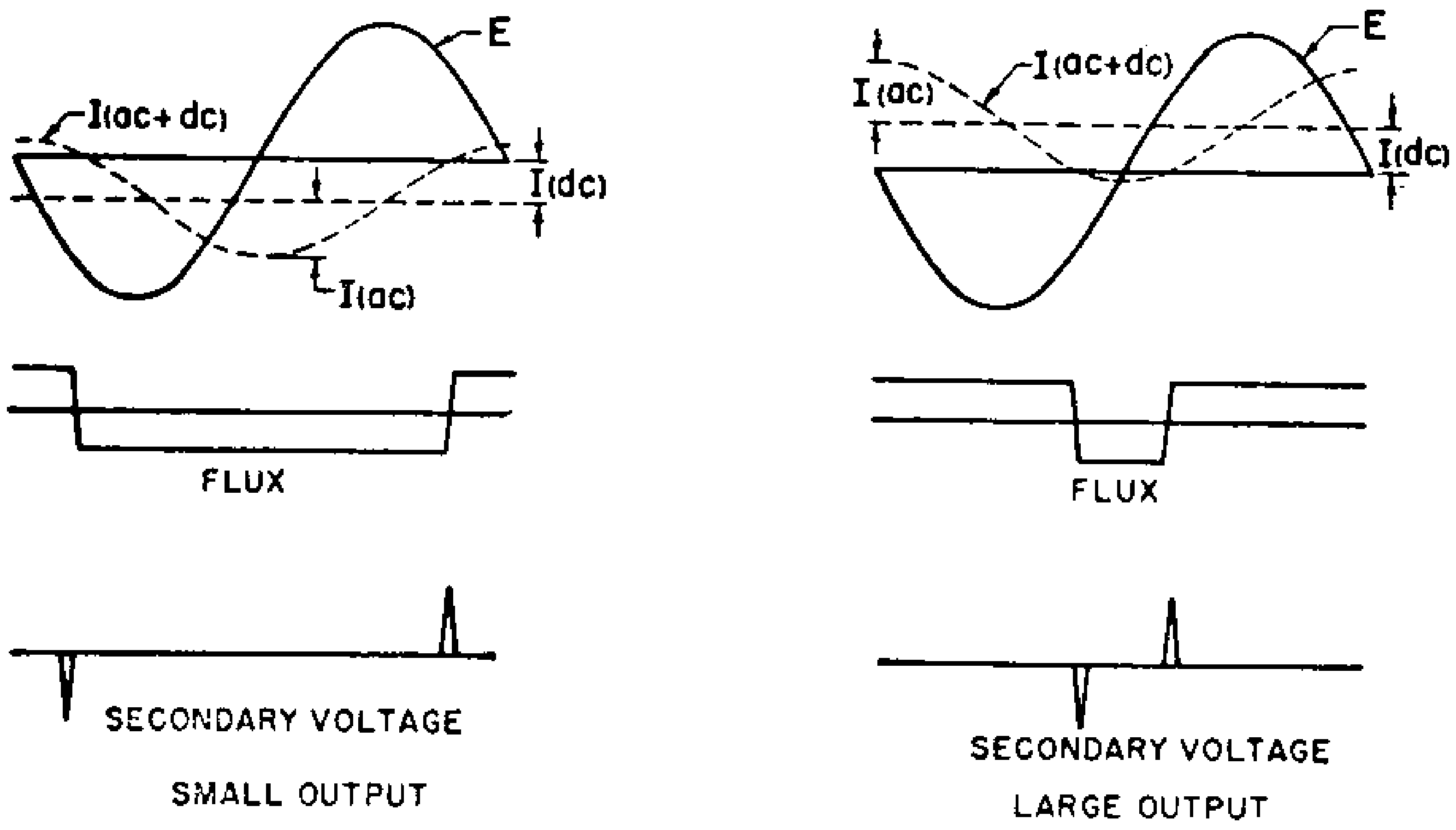


Figure 32

(f) Varying the magnitude of half wave rectified current through the primary of a grid transformer, so that the decaying negative voltage pulse on the next half cycle controls the firing of the control tube grid (Fig. 33).

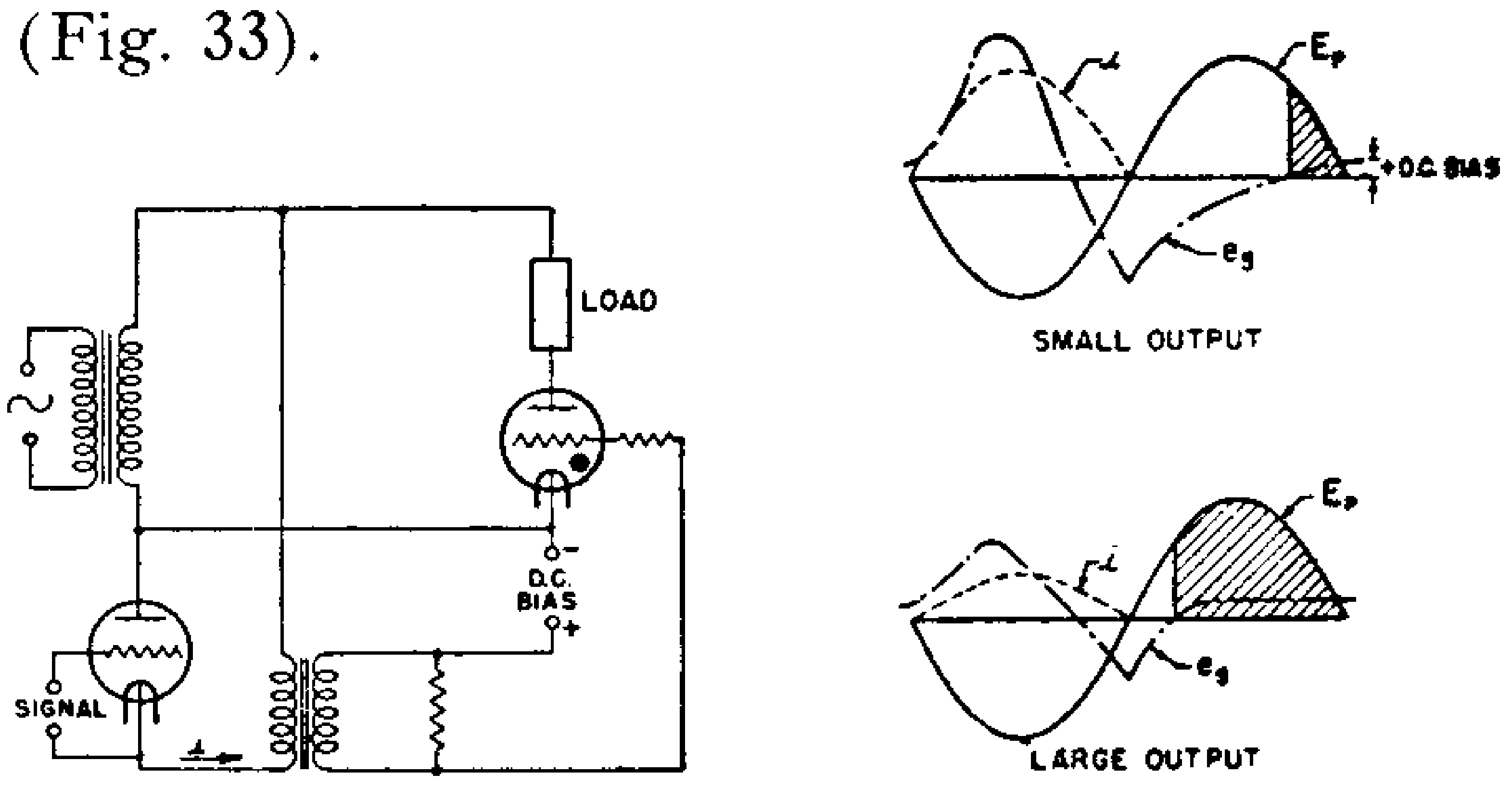


Figure 33

(2) GRID CIRCUIT STABILITY CONSIDERATIONS[12]

Having obtained the signal voltage and used it to give the desired firing point control, noise, in its general sense, coming from various sources must be kept from interfering with the desired control. There are several complicating factors present with gas tubes that are usually ignored in high vacuum tube circuit design. First, noise which lasts only a few microseconds may misfire a tube for a whole half cycle and become troublesome, whereas in audio work the duration of the noise would be too short to be noticed. Second, there are more sources of disturbing influences from the nature of the circuit. The sources may be considered individually.

(A) Sources of Noise

(a) While the tube is conducting anode current the grid becomes a probe electrode immersed in the main arc discharge. Ions and electrons from the main arc tend to maintain the grid at a potential of about +2 volts relative to cathode. The actual grid potential varies with instantaneous grid current, anode current, and tube history. Figure 34 gives the variations for a specific EL C6J.

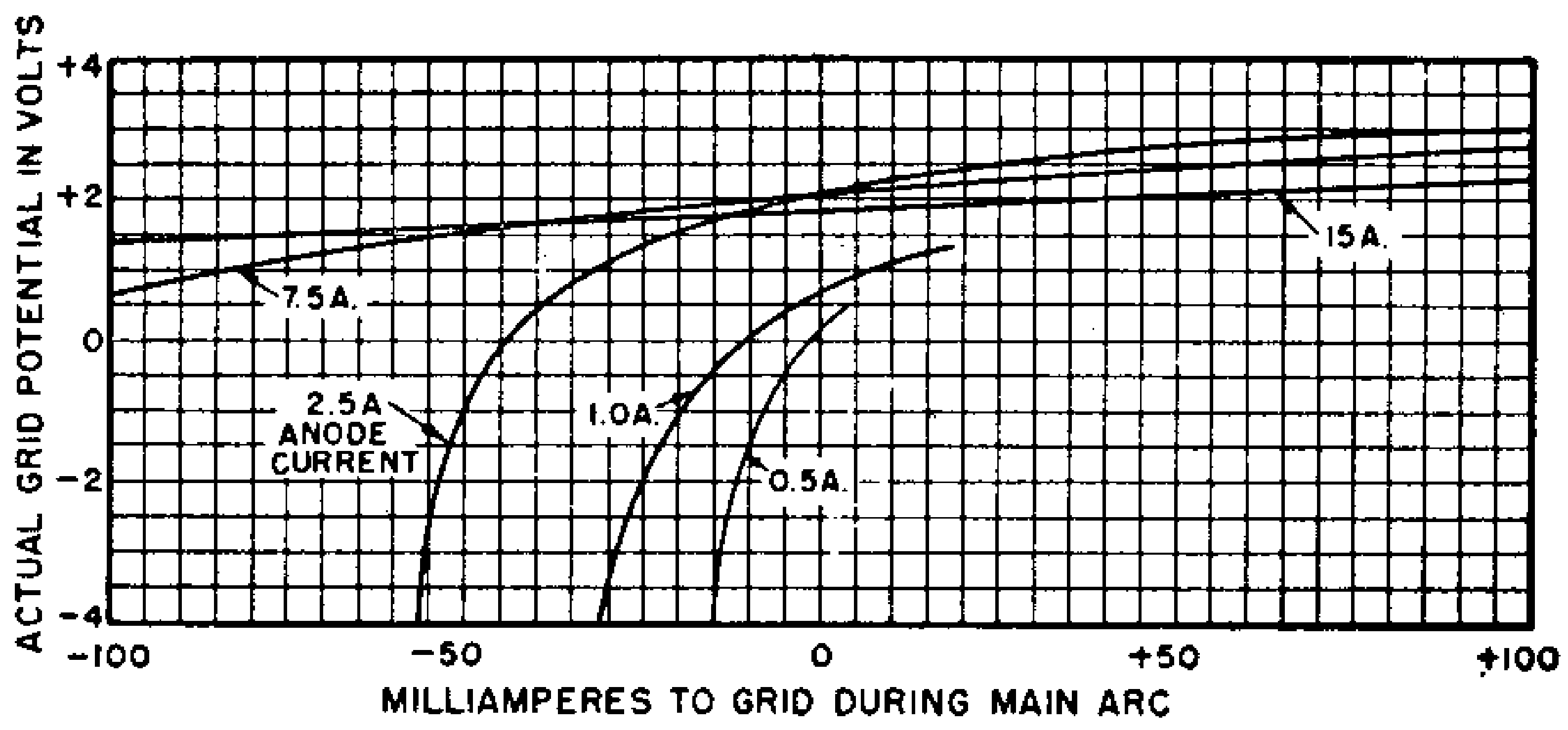


Figure 34

If any capacitances or inductances receive stored energy by reason of the grid current flow during this period, which is not dissipated before the next cycle, there is a carry-over effect which appears to change the firing on the next cycle due to current flow on preceding cycles.

In rectifiers operating in the continuous current region the effect of grid current to the conducting tube disturbs the signal of the tube about to enter conduction if there are grid circuit impedances common to the two tubes.

Current may flow to the grid during the inverse cycle if it becomes positive and cause carry-over effects. The current voltage curve of the grids of a typical EL C6J is shown in Figure 35.

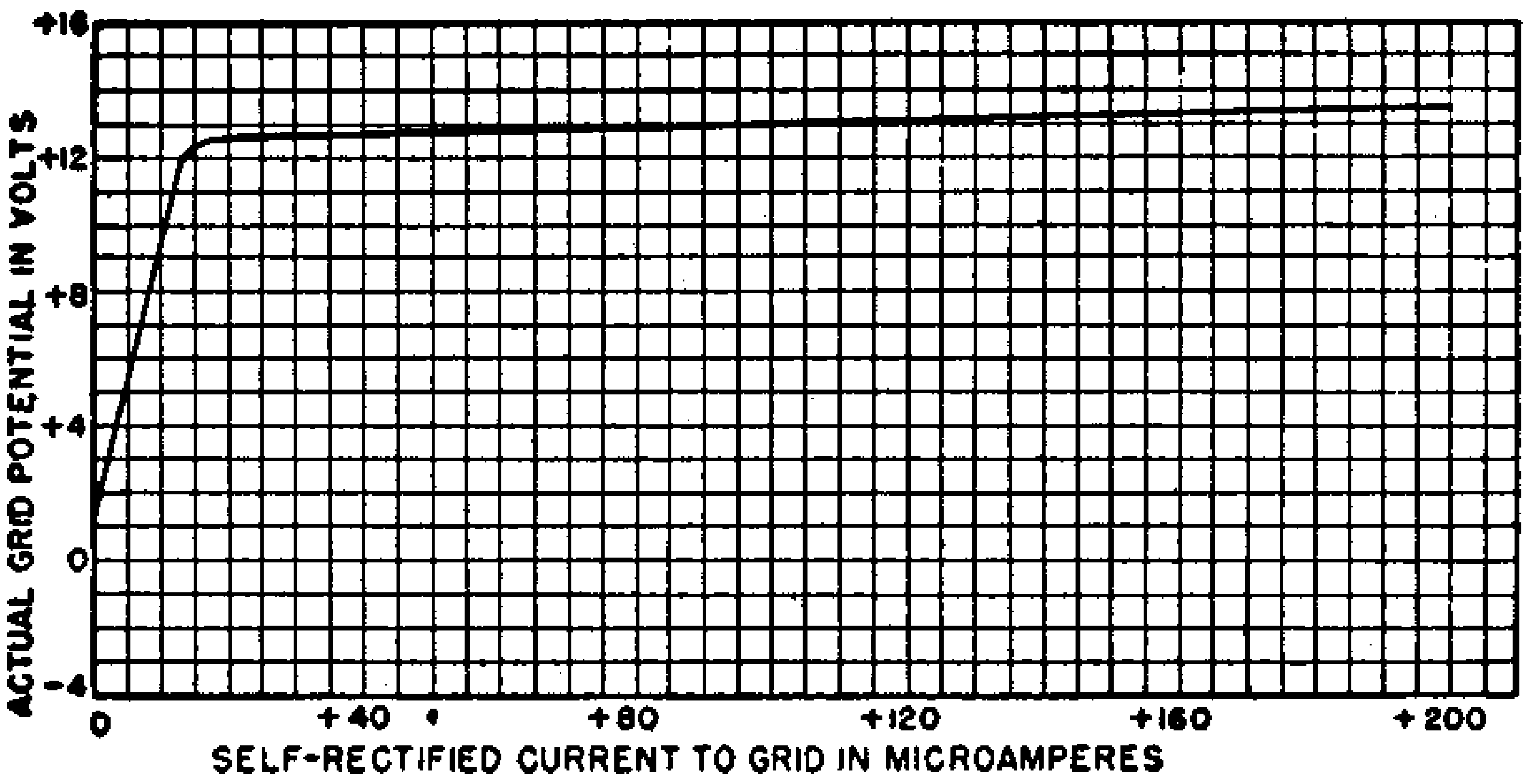
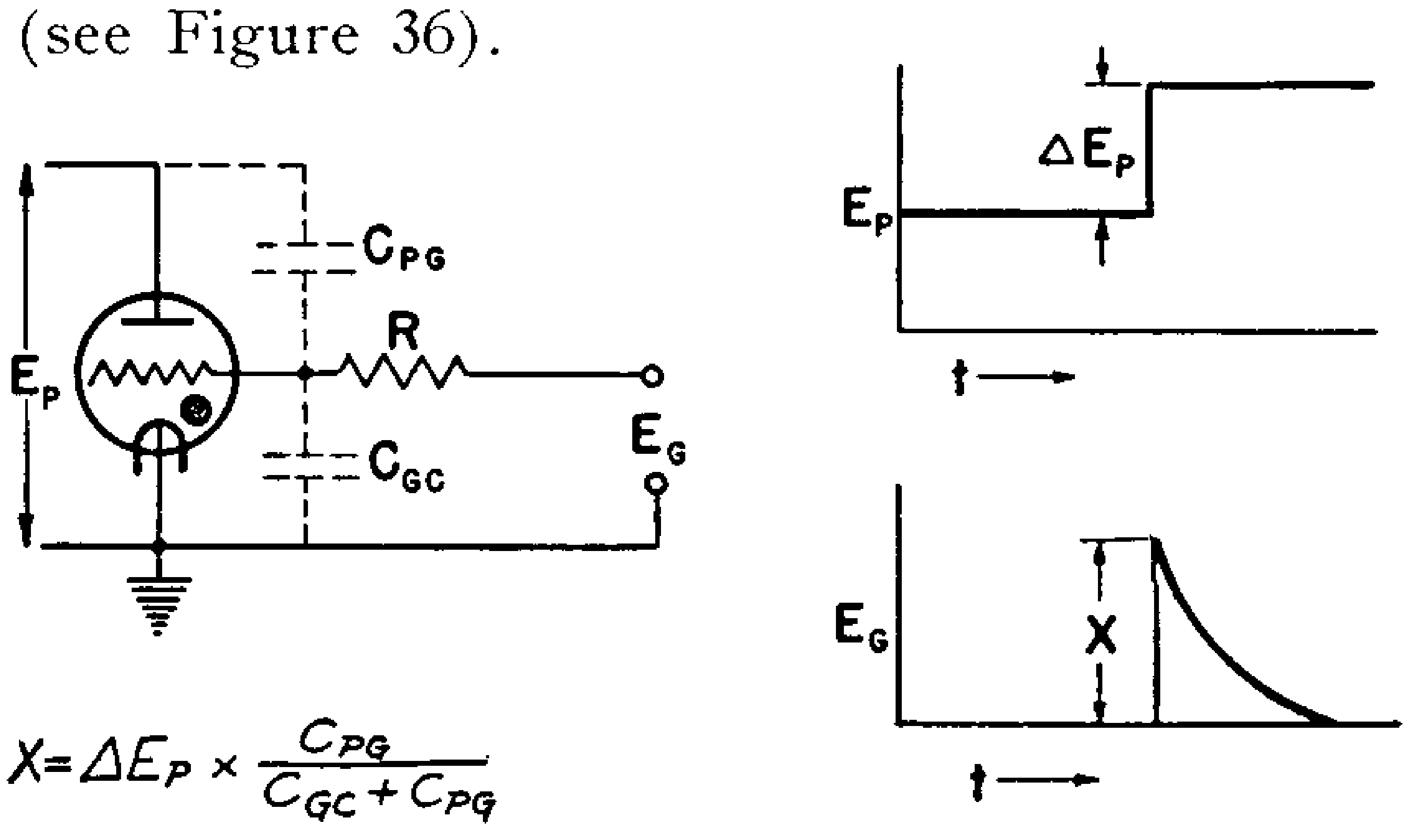


Figure 35

Above approximately 10V an arc is established to the grid. A steady arc drop appears between grid and cathode, and any remaining voltage is absorbed in other parts of the grid circuit.

(b) A steep transient wave front which increases the anode voltage abruptly will induce a momentary grid voltage, by the plate-grid to grid-cathode capacitance ratio (see Figure 36).



$$X = \Delta E_P \times \frac{C_{PG}}{C_{GC} + C_{PG}}$$

Figure 36

For instance a 10% increase in peak forward voltage due to commutator sparking, radio frequency, or switching a transformer on the supply line, for an EL C6J tube with 650V applied peak forward voltage would give (650 x 0.10) x (4/25) = +10.4V grid voltage instantaneously, unless a grid-cathode capacitance (approximately .0005 uf) is added in which case the instantaneous noise would be 0.5V. The capacitor should be connected directly between grid and filament, as close to the tube terminals as possible.

Transient voltages are often picked up in the grid circuit via the primary to secondary capacitance of grid transformers, or through the wiring capacitance to an undergrounded chassis. A typical case is encountered in a back-to-back connection with a-c. bias and signal (Fig. 37).

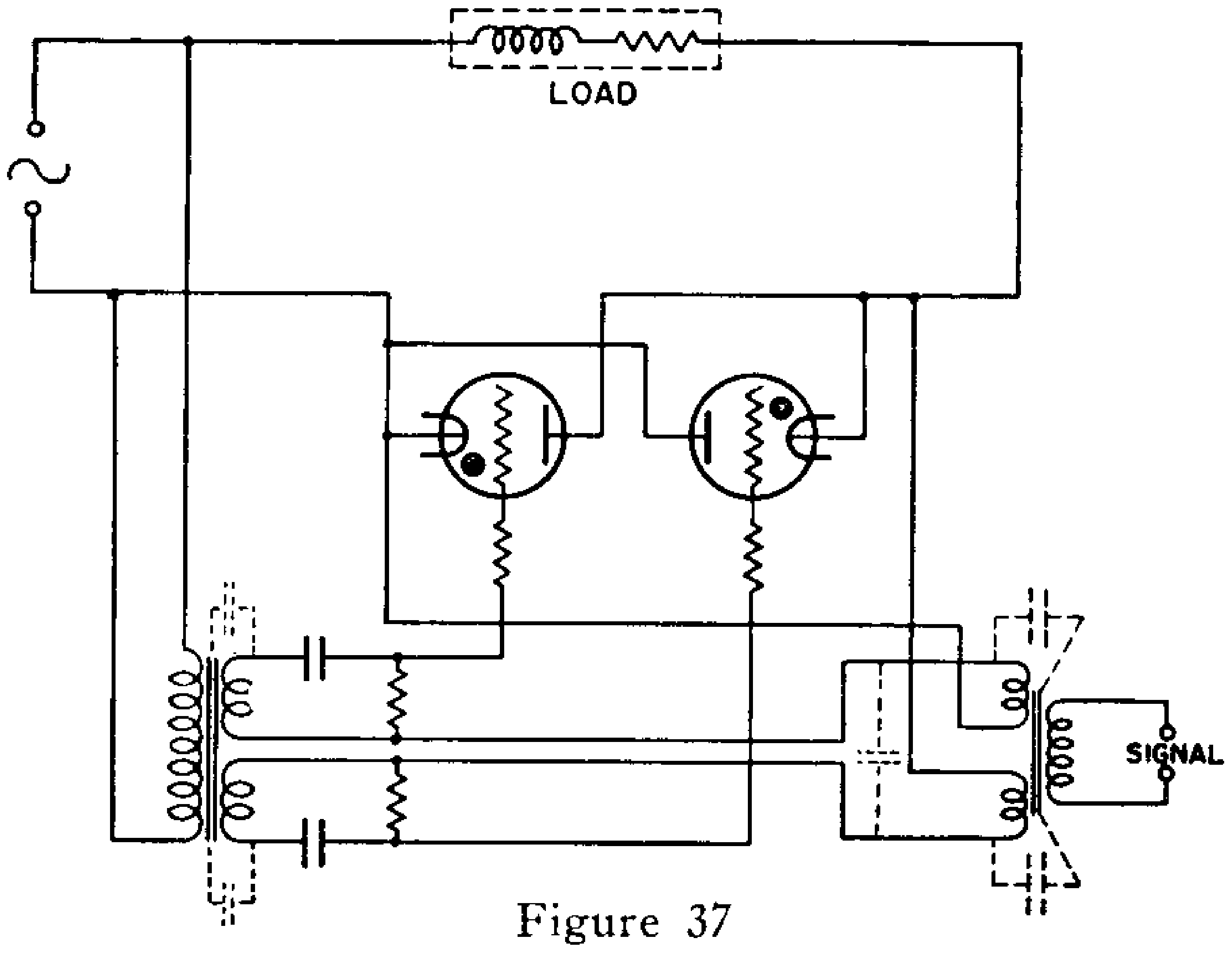


Figure 37

As load current dies out through one tube it generates a voltage in the load inductances. When conduction finally ceases this voltage collapses abruptly. The surge of voltage caused by this collapse is in a direction to produce positive anode voltage on the other tube. The stray capacitances between the grid transformer secondary windings and between these windings and ground must be charged by this surge of voltage. Charging current for these stray capacitances flows through the impedance of the bias windings, creating a momentary drop in the bias voltage. The effect appears as noise in the grid circuit of the tubes at the current-zero instant. Electrostatic shielding of the grid circuit wiring, or of grid transformer windings, minimizes this effect when the shields are connected to the related tube cathodes, not to ground.

A control rectifier which operates over a range including both continuous and discontinuous current, suffers an abrupt change in trigger point because of the change in instantaneous anode voltage at the transition. Also the resulting transient change of voltage on the stray grid circuit capacitances at the current change-over point may be a source of noise at the grid.

A change of signal due to line regulation caused by the current drawn by the conducting tube may become an annoying source of noise for the tube about to enter conduction.

(B) Anti-Hunt

A closed loop system, i.e. one where the signal controls a tube which powers a device to change the signal, often has a tendency to hunt. The matter has been explored mathematically and practically most extensively, and numerous books are available for advanced treatment. However, the methods by which engineering improvement may be made are simply expressed.

(a) Every effort should be made to make the signal report changes in a time that is short compared with the desired response time.

(b) As the sensitivity, or the speed of response is pressed upward, more power is spent in changing the stored energy in the load inertia, relative to the power going into work. Hence effective inertia should be kept at a minimum.

(c) Rate circuits, which partially adjust the grid signal in proportion to the rate of change of signal, and compensate for inertia in the load by directing the power at the rate necessary to readjust the stored energy to the required value, may be included.

(d) Rates of change of signal that are large compared with the possible response of the overall system are effectively noise, and should be averaged out.

Life Expectancy

All of the factors affecting life expectancy mentioned for rectifiers apply equally well for grid control rectifiers. However, the complexity of control circuits and the additional ratings make a careful design check more essential, to be sure that no tube rating is being unknowingly exceeded under likely operating conditions, or that a slight shift in tube characteristic will not cause unsatisfactory performance.

In general, the design of grid control rectifiers has resulted in this class of unit having on the average longer tube life than the usual uncontrolled unit. A life less than 3,000 hours definitely indicates either a defect in the tube or its application. Lives in excess of 10,000 hours are common.

It is usually economically impractical to start grid control rectifier tubes regularly with less than recommended heating time. However, the time delay may bias the grid to prevent anode conduction instead of opening the d-c. circuit.

Laboratory Techniques

An oscillograph arranged to show d-c. potential, either by a good d-c. amplifier or by connecting directly to the deflection plates without a blocking capacitor, is a great assistance during unit development. A potentiometer may conveniently be connected to attenuate the voltage being observed or to be cut out entirely when observing grid voltage. It sometimes is convenient to build oscilloscopes with very low accelerating voltage (300V), sacrificing brilliance for d-c. sensitivity. By calibrating the deflection, tube arc drops and grid voltages may be conveniently measured while the tube is operating normally. Simultaneous viewing of grid and anode voltages may be made without an electronic switch, by connecting the anode to cathode voltage on one set of plates and the grid to cathode voltage on the other.[8] Oscilloscopes have been built with low stray capacitance from the ground lead to the a-c. power supply. The greater integrity of their display is very comforting when analyzing a complex circuit.

In working with closed loop control circuits the effect of noise pick up may be separately studied by opening the loop, varying the input signal and also the power load to look for rough or irregular operation. Another precaution is to adjust the signal to the dead zone and apply a signal impulse for just long enough to fire one-half cycle. If regenerative pick up is present two or more conductive cycles may be observed on the scope.

The measurement of high commutation rates should be considered. A triggered sweep oscilloscope with an internal delay line, is a great convenience, though usually not essential. It may be used with only normal precautions for such instruments. It may be calibrated with known voltages for the voltage scale and with a capacitor resistor network, or a frequency standard, for the time scale. Then, connected between successively firing anodes, the recovery voltage rate may be read directly and the current decay rate computed by dividing the total d-c. current by the current commutation time in microseconds as read on the triggered sweep oscilloscope. The observed picture is as follows:

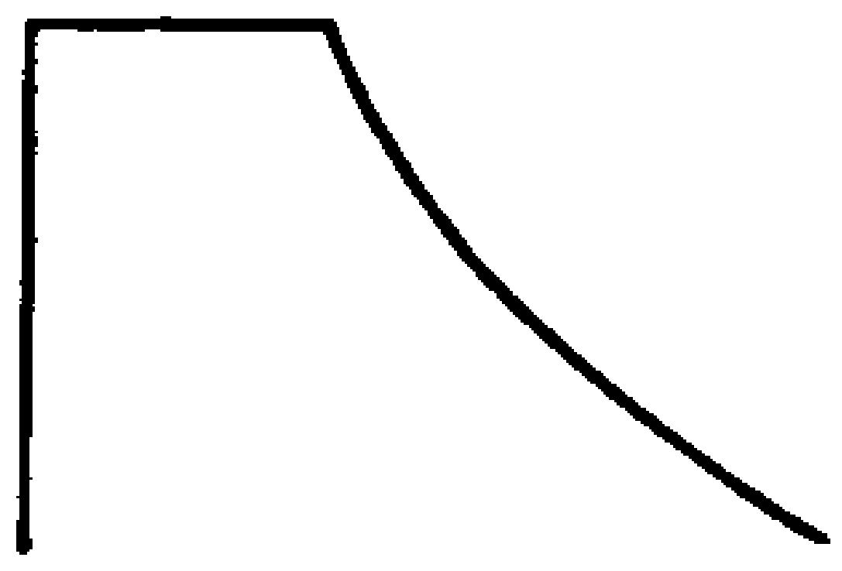


Fig. 38

If an oscilloscope is used to measure the rates, a noninductive voltage divider of sufficiently low resistance to avoid capacitance distortion may be connected between successively firing anodes. For the single phase full wave circuit the observed picture will be as in Fig. 39 (commutation time exaggerated).

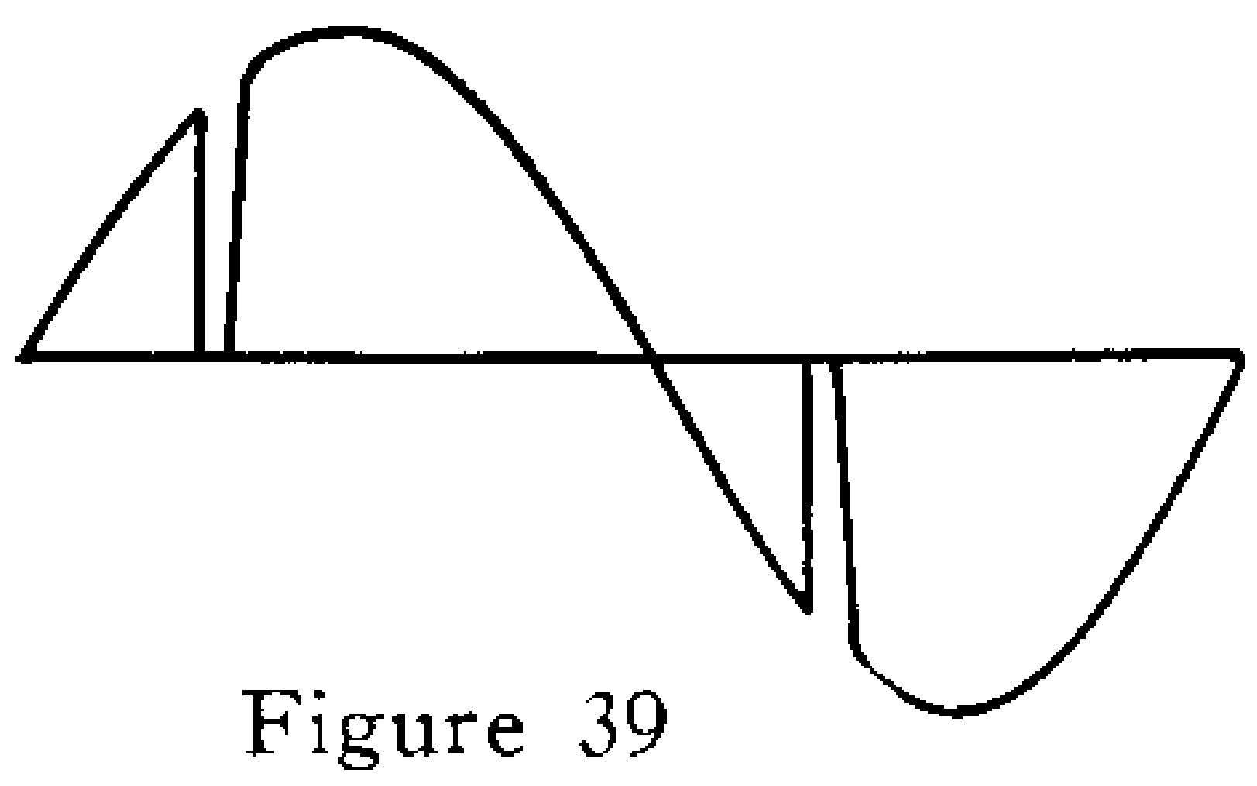


Figure 39

Then the sweep frequency may be increased to some multiple of the supply frequency. (A dark hood is often necessary over the scope.) The picture is then

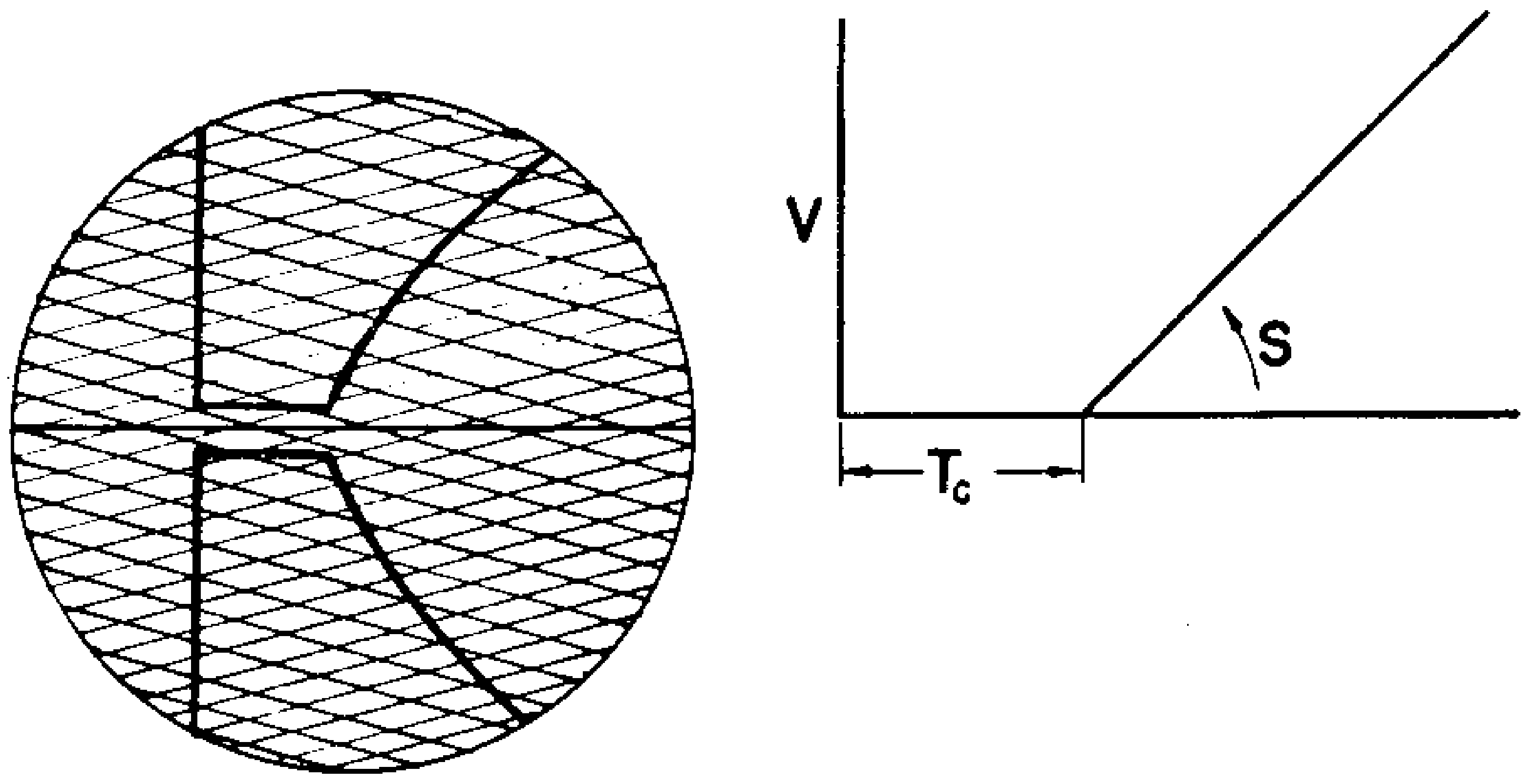


Figure 40

The slope S and time Tc are observed and recorded. Without changing the sweep frequency the scope is calibrated with a sine wave of known voltage and frequency. The slope of the sine wave near the axis (equal to $2\sqrt{2}\pi fE$ where E is the r.m.s. voltage from anode to anode and f the frequency) is multiplied by the ratio of the measured slope S, to the sine wave slope at the horizontal axis, to obtain the desired voltage recovery rate. Also, knowing the volts per microsecond and the vertical deflection per volt, the horizontal deflection per microsecond may be computed. The distance Tc is thus converted to microseconds. The measured load current divided by this time in microseconds is the average current commutation rate.

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CROSS REFERENCE LIST

EL RECTIFIER and THYRATRON TUBES

and Applicable RETMA or MIL-E-1B Specifications

Rectifiers

EL Type	JAN Type	RETMA Type
EL 1C	3B22	3B22
EL 3B	3B*	6013
EL 3C	4B24	4B24
EL 3CF	----	----
EL 5B HD	4B23	4B23
EL 5B Std	4B22	4B22
EL 6B	----	5892
EL 6C	6C*	----
EL 6CF	4B25	4B25
EL 6F	----	6015
EL 16B	16B*	----
EL 16F	----	----
EL 302.5	3B21	3B21

Thyratrons

EL Type	JAN Type	RETMA Type
EL C1A	C1A	----
EL C1B	---	3C31
EL C1B/A	5664	5664
EL C1J/A	---	5683
EL C1K	C1K*	6014
EL C1K/B	---	----
EL C3H	---	----
EL C3J	---	5632
EL C3J/A	5684/C3J/A*	5684
EL C3J/K	----	----
EL C3R14	C3R14	----
EL C3P14	----	----
EL C4J	----	----
EL C5F14	----	6231
EL C5B	C5B	5C30
EL C6A	C6A	----
EL C6C	----	----
EL C6J	----	5C21
EL C6J/A	5685/C6J*	5685
EL C6J/F	----	----
EL C6J/K	----	----
EL C6J/KF	----	----
EL C6L	5528/C6L	5528
EL C6P	----	----
EL C16J	5665	5665

*Preferred type (MIL-STD-200)

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EL RECTIFIER

and

GRID CONTROL RECTIFIER TUBES

PRICE LIST I - PREFERRED TYPES

Full-Wave Rectifiers	Max. Average DC Current Per Tube	Max. Peak Inverse Voltage	List Price
EL 1C	1.0	725	$ 7.60
EL 3C	2.5	725	8.90
EL 6C	6.4	725	16.60
Half-Wave Rectifiers			
EL 3B	2.5	920	8.60
EL 6B	6.4	920	11.05
EL 6F	6.4	920	12.40
EL 16F	16.0	620	24.30
Grid Control Rectifiers		**Max. Peak Forward Voltage**	
EL C1B/A	1.0	750	10.40
EL C1K	1.0	1000	10.40
EL C3J	2.5	750	12.10
EL C3J/A	2.5	1000	15.10
EL C6C	6.4	2000	43.20
EL C6J	6.4	750	29.30
EL C6J/A	6.4	1000	30.30
EL C6J/F	6.4	1000	30.80
EL C16J	18.0	1000	57.90

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EL RECTIFIER and GRID CONTROL RECTIFIER TUBES

PRICE LIST II

(For preferred types see Price List I)

SPECIAL TYPES

Grid Control Rectifiers		Max. DC Current	Max. Peak Forward Voltage	List Price
EL C1K/B		1.0	2000	$ 12.50
EL C3H	(Short Deionization Time)	2.8	1100	20.40
EL C3J/K	(High Commutation Factor)	2.5	1000	21.30
EL C3P14	(14V. Heater-Isolated Cathode)	3.0	1100	42.60
EL C3R14	(14V. Heater-Isolated Cathode)	3.0	500	42.60
EL C4J		4.0	500	19.40
EL C5F14	(14V. Heater-Isolated Cathode)	5.0	500	39.10
EL C6J/K	(High Commutation Factor, Base Mounted)	6.4	1000	32.90
EL C6J/KF	(High Commutation Factor, Bracket Mounted)	6.4	1000	33.30
EL C6P	(Short Deionization Time)	6.4	1000	32.20
EL C16J/A		18.0	1250	63.70

NOT RECOMMENDED FOR NEW DESIGN

Full-Wave Rectifiers	Max. Average DC Current Per Tube	Max. Peak Inverse Voltage	List Price
EL 3CF	2.5	725	$ 8.90
EL 5B HD	5.0	425	23.20
EL 5B Std	5.0	340	21.40
EL 5C	5.0	85	14.10
EL 6CF	6.4	725	16.60
EL 10A	9.0	115	22.20
EL 22.5	2.5	100	8.40
*EL 302.5	1.0	500	10.10
Half-Wave Rectifiers			
EL 16B	16.0	620	24.30
EL 60B	50.0	1250	151.50
Grid Control Rectifiers		**Max. Peak Forward Voltage**	
EL C1A	0.64	170	11.90
**EL C1B	1.0	450	9.60
***EL C1J	1.0	450	9.60
***EL C1J/A	1.0	750	10.90
EL C3A14	3.0	750	42.60
EL C5B	5.0	750	39.10
EL C6A	6.4	300	32.30
EL C6L	6.4	350	32.20
EL C6M	6.4	1000	31.10

*EL 302.5 is directly replaceable by EL 1C
**EL C1B is directly replaceable by EL C1B/A
***EL C1J and EL C1J/A are usually replaced by EL C1K.

Data sheets for the above types will be sent upon request.

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PRICE DISCOUNT SCHEDULE

(Price List I - Preferred Types)

ELECTRONIC UNIT MANUFACTURERS are purchasers of EL Rectifiers or EL Control Rectifiers who incorporate such Rectifiers in electronic equipment of their own manufacture.

AUTHORIZED DISTRIBUTORS are appointed by Electrons, Incorporated and carry stocks of EL Rectifiers and EL Control Rectifiers.

DEALERS are purchasers of EL Rectifiers or EL Control Rectifiers for resale who do not classify as Distributors under the above definition.

Rectifiers	**List Price**	**Electronic Unit Manufacturer's Discount**	**Dealer's Discount**	**Authorized Distributor's Discount**
EL 1C	$ 7.60	30%	10%	30%
EL 3B	8.60	30%	10%	30%
EL 3C	8.90	30%	10%	30%
EL 6B	11.05	30%	10%	30%
EL 6C	16.60	30%	10%	30%
EL 6F	12.40	30%	10%	30%
EL 16F	24.30	30%	10%	30%
Control Rectifiers				
EL C1B/A	10.40	30%	10%	30%
EL C1K	10.40	30%	10%	30%
EL C3J	12.10	30%	10%	30%
EL C3J/A	15.10	30%	10%	30%
EL C6C	43.20	30%	10%	30%
EL C6J	29.30	30%	10%	30%
EL C6J/A	30.30	30%	10%	30%
EL C6J/F	30.80	30%	10%	30%
EL C16J	57.90	30%	10%	30%

ALL PRICES ARE F.O.B. NEWARK, NEW JERSEY AND ARE SUBJECT TO CHANGE WITHOUT NOTICE. TERMS ARE 1% TEN DAYS ON ACCOUNTS OF APPROVED CREDIT.

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