INDUSTRIAL ELECTRONICS HANDBOOK

INDUSTRIAL ELECTRONICS HANDBOOK

BY

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WITH A FOREWORD OF

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FOREWORD

The word electronics has, only very recently, made its first appearance in the Oxford English Dictionary. Few modern words are, however, more firmly established in use, either colloquially or in the literature of applied science. The utility of the word is unquestionable, but its very usefulness is already rendering it difficult to limit it satisfactorily in scope and application.

Essentially the subject of electronics deals with electric circuits in which the current is controlled in one respect or another by devices such as thermionic valves, gas filled relays, or photo-electric cells, but there are now, in addition, the rapidly developing techniques of current control by semi-conductor devices such as the transistor. This book is concerned with industrial electronics and, by accepted convention, this means electronic circuits in applications other than those for purposes of telecommunication. Such a division is not only a practical necessity but it has long been recognised in the general field of electrical engineering that power and telecommunication constituted the two main and distinct branches of the applications of electricity. Overlapping territories have, however, become a common feature of the modern scientific scene and so with electronics there can be no clear boundaries of demarcation. Automatic computors which have been described as being concerned with the "processing" of information are already often associated with electromechanical systems of considerable power and no doubt in the future will be increasingly utilised in the automatic control of industrial processes. The field taken by the author of this book as his province is one which, important as it already is, must increase in influence as time goes on, for, within it, lies the most potent factor for the increasing of productivity in industrialised communities. That is a matter, the importance of which to the progress of civilisation, needs no argument or demonstration.

The reader will find in the present book first a sound treatment of the scientific principles of vacuum and gas-filled electronic tubes and their basic circuits. It is the second part of the book which deals with applications and these have been judiciously selected to illustrate in a clear fashion the more important principles of application which have so far been developed.

The book may be said to constitute a most satisfactory and trustworthy introduction and guide to a branch of electronic work which already has an extensive specialised literature. Coming, in authorship, from an organisation which has been associated in such a distinguished way with research and development in the electronic field, it is natural to expect to find a treatment of the subject which is both illuminating and authoritative and in this expectation the reader will not be disappointed.

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PREFACE

Developments during the past few years have abundantly proved how great are the advantages, both technical and economic, which can be gained by the adoption of electronic methods, that is to say processes and methods of control based upon the application of electronic tubes in their many and diverse forms.

It must be admitted, however, that in certain industries the introduction of applied electronics is but slow. This tardiness is almost certainly due to the fact that there are still many engineers and technologists who have not, as yet, been fully informed as to the possibilities, or even the nature, of industrial electronics. It is quite natural that plant and production engineers in, for example, the textile, steel and chemical industries, should view with a certain reserve, amounting almost to suspicion, processes and methods with which they are quite unfamiliar, and will show some reluctance to the adoption of an electronic aid in place of some older and well-understood device.

It was mainly this reason that induced me to write this book, which is primarily addressed to works engineers engaged in every branch of industrial production. It is also hoped that those studying for entry into the technical professions will also find the book a useful elementary introduction to the whole subject of industrial electronics, a knowledge of which is today essential to every industrial engineer.

To this end, much thought has been devoted to the methods of exposition and presentation. It has, for example, been considered especially important to include detailed descriptions and explanations of a number of circuits which have been used in industrial practice and have proved their worth. In many cases very comprehensive data and specifications of the values of the component parts have been included.

I am greatly indebted to numerous firms engaged in industrial electronics for permission to reproduce photographs and to quote from their technical publications. Special thanks are due to Philips, Eindhoven, for their valuable support, without which this book would never have been published. I also wish to express my thanks to Mr. Harley Carter, A.M.I.E.E. of Mullard Ltd., London, who prepared the English text, and to Mr. H. E. Kater of the Electronic Tube Division of Philips, Eindhoven, for his assistance in supervising the general lay-out and the production of the illustrations.

Hamburg, October 1953 The Author

TO THE SECOND EDITION

This second edition has been considerably enlarged and is again entirely up to date. The recently introduced E 1 T decade counter tube, for example, is described in detail. Several counter circuits equipped with this tube and various applications of these circuits are discussed. Full particulars are given on the design of industrial rectifier circuits, including the design of controlled rectifiers. The section on electronic motor control has been extended by including, for instance, a description of electronically controlled Ward-Leonard systems. Finally various types of electronic apparatus for special purposes have been dealt with, such as stabilized supply units, electronic dust precipitators, and so on.

As a result of inserting this new material, the present edition is considered to be so exhaustive as to justify the addition of the word HANDBOOK to its title.

I wish to make a special acknowledgement to Mr. H. E. Kater of the Electronic Tube Division and Mr. D. J. Mitchell of the Translation Department – both of Philips Eindhoven – under whose care this edition was prepared.

Hamburg, October 1956. The Author

PREFACE TO THE THIRD EDITION

As the second edition of the Industrial Electronics Handbook, like the first, has sold out within so short a time, the Philips Technical Library has decided to issue a third edition. In view of the increasingly important role played by active semiconductor elements in industrial electronics, it seemed a suitable opportunity to add a short paragraph regarding the operation and the elementary circuit technique of transistors. A few additional special circuit arrangements have, moreover, been included. I hope that the third edition will meet with the same success as the two previous editions.

Hamburg, October 1958. The Author

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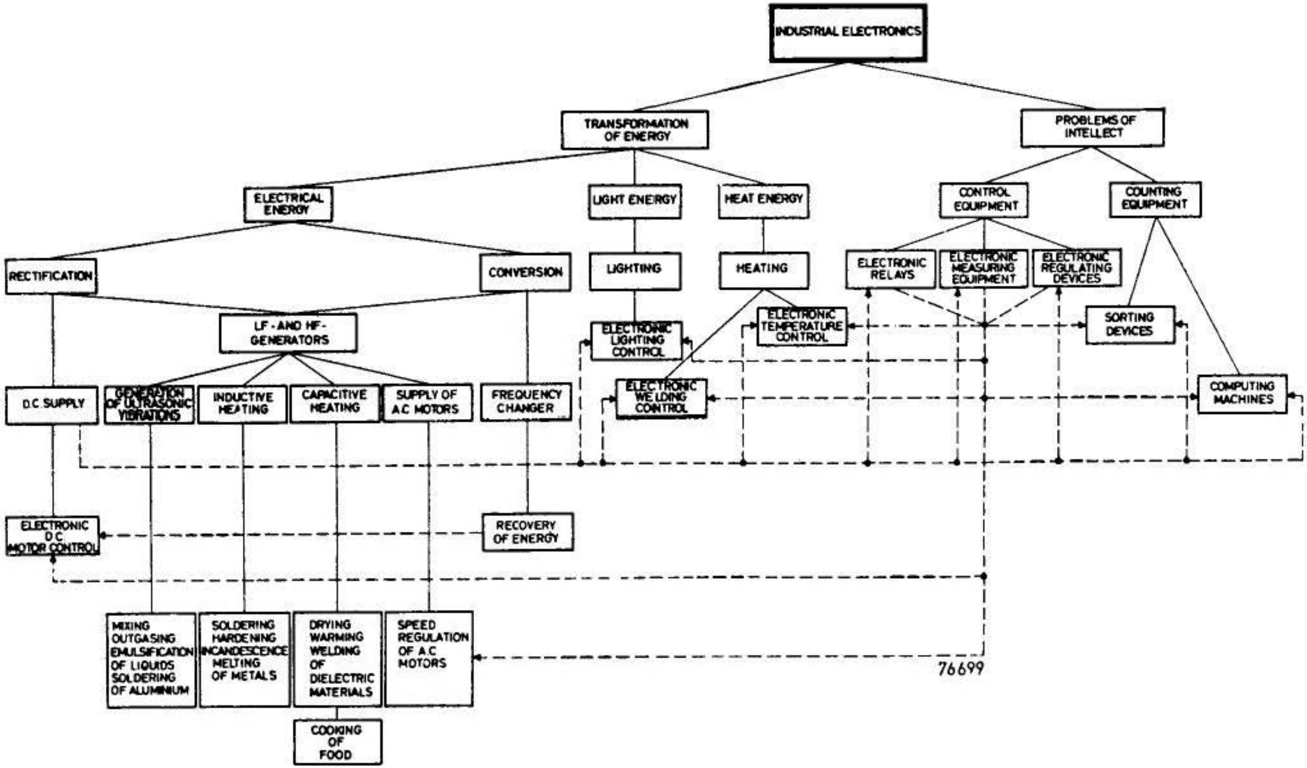
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TRANSFORMATION OF ENERGY
PROBLEMS OF INTELLECT
ELECTRICAL ENERGY
LIGHT ENERGY
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COUNTING EQUIPMENT
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LIGHTING
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ELECTRONIC RELAYS
ELECTRONIC MEASURING EQUIPMENT
ELECTRONIC REGULATING DEVICES
LF - AND HF - GENERATORS
ELECTRONIC LIGHTING CONTROL
ELECTRONIC TEMPERATURE CONTROL
SORTING DEVICES
ELECTRONIC WELDING CONTROL
COMPUTING MACHINES
D.C. SUPPLY
GENERATION OF ULTRASONIC VIBRATIONS
INDUCTIVE HEATING
CAPACITIVE HEATING
SUPPLY OF A.C. MOTORS
FREQUENCY CHANGER
ELECTRONIC D.C. MOTOR CONTROL
RECOVERY OF ENERGY
MIXING OUTGASING EMULSIFICATION OF LIQUIDS SOLDERING OF ALUMINIUM
SOLDERING HARDENING INCANDESCENCE MELTING OF METALS
DRYING WARMING WELDING OF DIELECTRIC MATERIALS
SPEED REGULATION OF A.C. MOTORS
COOKING OF FOOD
76699

INTRODUCTION

This book deals in particular with electronic circuits employing highly evacuated or gas-filled discharge tubes, i.e. devices in which electrons move through free space instead of in a metallic conductor. Such devices include not only the familiar amplifying tube so widely used in radio and television engineering, but also photocells, cathode-ray tubes, X-ray tubes, and gas-filled rectifying tubes with or without grid control; even fluorescent lamps should be classed as electron tubes.

During the last ten or twenty years the potentialities of electronic techniques have gained increasing recognition, especially in industry. These techniques make possible improved and more efficient manufacturing methods and the accurate control and regulation of almost every kind of process.

For example, by means of electronic control, mechanical drives can be given almost any desired speed-torque characteristics; the control apparatus being to all intents and purposes inertialess, it is practically instantaneous in action. Moreover it consumes negligible power. Feed drives of machine tools, [illegible] motor drives in rolling mills, spinning machines, wire drawing mills, lifts and many other drives may be given the required characteristics by means of electronic control. Electronic circuits incorporating photocells or other pick-up devices can be employed for signalling, sorting, inspection or counting in mass-production plants, in chemical processes, in transportation equipment and in other industrial operations. Electronic timers in conjunction with electronic switches can control the process timing of welding machines with high precision, and thus contribute to improved quality. Electronically generated H.F.-energy offers new possibilities in the woodworking and plastic industries for the economical production of furniture, plywood and plastic articles. Steel hardening and soldering or smelting of metals by H.F.-energy increases the economic production of metal goods and leads to improved quality.

Generally speaking, electronics can assist the industrial engineer in the solution of two fundamental types of problem; (1) the transformation of electrical energy into other forms of energy; and (2) the execution of processes analogous to the exercise of intellect, for instance, measuring, counting, sorting, etc.

A similar division of problems into two fundamental groups can equally be found in other fields, for example, in medicine (therapeutics and diagnosis), in lighting (illumination and indication) and in telecommunications (carrier generation and modulation). For industrial electronics, these two groups of problems are depicted in the diagram on the opposite page, which also indicates a large number of practical applications and their mutual relationships. Most of these applications are dealt with in this book.

As result of the growing importance of electronics in the industrial field, it has been necessary to develop tubes specially designed for industrial use. Radio and telecommunications call mainly for voltage amplifying tubes, for power amplifiers of comparatively low output, and for tubes capable of generating unmodulated or modulated H.F. oscillations of medium power. These requirements are easily met by high vacuum amplifying and transmitting tubes. In industry, however, control or switching operations on comparatively large currents will very often be needed. For these purposes high vacuum tubes are less suitable, and gas-filled tubes and valves of various kinds are then employed.

Both vacuum and gas-filled tubes and many other electron devices are used in industrial applications, and the first part of this book is therefore devoted to these tubes and their basic circuits. In the second part practical circuits and their applications are described.

PART I

The Tubes and Their Basic Circuits

1. AMPLIFYING AND TRANSMITTING TUBES

The essential elements of a high vacuum tube are a cathode and an anode, which are mounted facing another and sealed in an evacuated bulb.

The cathode consists of a material which readily emits electrons when heated. The cathode of transmitting tubes often consists of a wire of pure or thoriated tungsten which is heated by a low voltage source to the temperature required for electron emission. Such cathodes are said to be directly-heated. The cathodes of amplifying tubes are usually formed of a nickel tube coated externally with a mixture of alkaline oxides — particularly barium and strontium oxide. Heating of this type of cathode is by a tungsten filament located within the nickel tube, which is therefore termed an indirectly-heated cathode.

The anode consists of metal or occasionally graphite. Its function is to collect the electrons emitted by the cathode. To ensure this, the anode is maintained at a positive potential with respect to the cathode.

In most types of tube one or more "grids" are located between the cathode and anode. These are wire spirals of suitable shape and size. Such a grid will govern the density of the electron stream flowing from the cathode to the anode, according to its potential with respect to the cathode. If, for instance, the grid potential is negative, the electron current may be greatly reduced or even entirely suppressed.

Fig. 1–1 shows the conventional diagrammatic representation of typical tubes, that on the left being the symbol for a directly-heated triode and that on the right an indirectly-heated pentode.

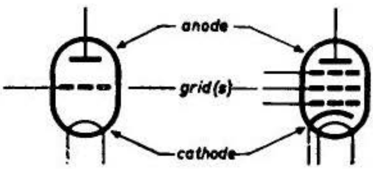


Fig. 1-1. Tube symbols (left: directly heated triode, right: indirectly heated pentode).

The construction of a pentode, i.e. an amplifying tube containing three grids surrounding the cylindrical cathode, is shown in fig. 1–2.

If the anode of a three-electrode tube (containing cathode, anode and one grid) is maintained at a positive potential (the anode voltage V_a) and a variable negative voltage V_g is applied to the grid, the value of the current I_a flowing to the anode can be plotted as a function of the grid voltage. A typical "I_a–V_g" diagram is reproduced in fig. 1–3. From this curve the amount by which anode current will change, if the grid voltage

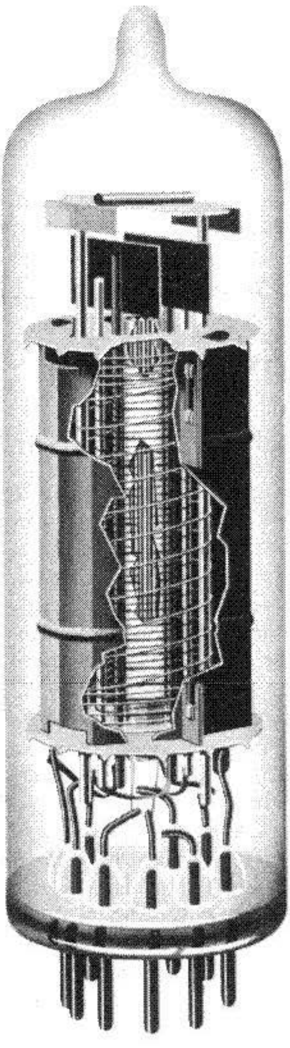


Fig. 1-2. X-ray photograph of a pentode amplifying tube (EL 84).

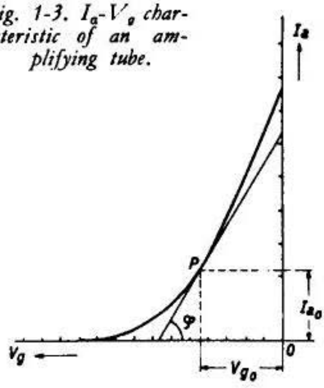


Fig. 1-3. I_a-V_g characteristic of an amplifying tube.

is modified by a given amount, can be ascertained. Obviously this relation is equal to the slope of the curve, i.e. the tangent of the angle formed by the positive x-axis of the graph and the tangent to the curve constructed at the point under consideration. The slope S may thus be defined as:

$$S = \tan\varphi = \frac{dI_a}{dV_g}, \tag{1.1}$$

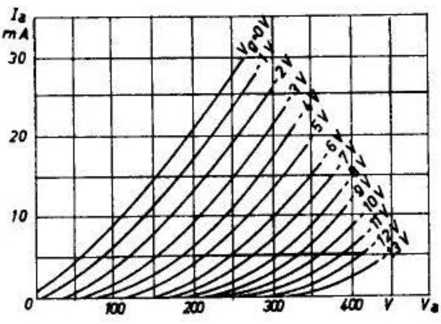


Fig. 1-4. I_a-V_a characteristics of an amplifying triode.

assuming the anode voltage to be held constant.

The slope has the dimension of a conductance, i.e. the reciprocal of a resistance, and is usually expressed in mA/V.

If the grid voltage is held constant, and the anode current is plotted as function of the anode voltage, the "I_a–V_a" diagram can be obtained (fig. 1-4) with V_g as parameter. Obviously the I_a–V_g diagram of a tube can easily be derived from its I_a–V_a diagram. If a given point is chosen on an I_a–V_a diagram and the tangent to it is constructed, the cotangent of the angle formed by the tangent and the positive x-axis of the graph represents the internal resistance of the tube at the given working point. It can be defined as

$$R_i = \frac{\mathrm{d}V_a}{\mathrm{d}I_a}, \tag{1.2}$$

the grid voltage being held constant. It should be pointed out that this resistance is the a.c. resistance of the tube, and must not be confused with the d.c. resistance which is equal to the quotient of the anode voltage and anode current at the working point, i.e.

$$R_{i=} = \frac{V_a}{I_a}. \tag{1.3}$$

The basic circuit of a tube operated as an amplifier is shown in fig. 1–5. The

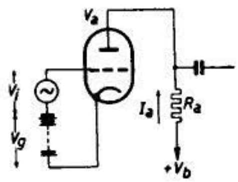


Fig. 1-5. Basic circuit of an amplifying stage.

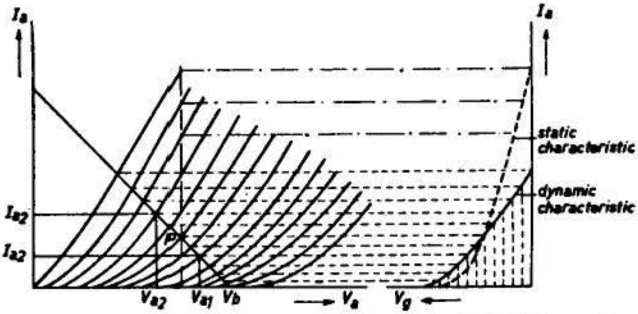


Fig. 1-6. I_a-V_a characteristics of a triode with load line and dynamic I_a-V_g characteristic.

control grid is given a fixed negative bias V_g; in addition the alternating input voltage V_i, which is to be amplified by the tube, is applied to the grid. The anode circuit contains an external resistance R_a across which there will be a voltage drop $I_a \cdot R_a$ depending upon the instantaneous value of the anode current. This voltage therefore varies in sympathy with the changing value of the input voltage V_i. The effective anode voltage is therefore:

$$V_a = V_b - I_a \cdot R_a, \tag{1.4}$$

where V_b is the direct supply voltage.

Equation (1.4) shows that I_a is a linear function of the anode voltage V_a, which may be plotted in the I_a–V_a diagram as a straight line (fig. 1–6). Evidently V_a is equal to V_b only when $I_a = 0$, and the effective anode voltage decreases as the anode current increases. It is therefore clear that the "static" I_a–V_g characteristic is not applicable when a signal is being amplified, and must be replaced by a "dynamic" characteristic of reduced slope.

The gain obtainable with a circuit as shown in fig. 1–5 is:

$$G = \frac{I_a \cdot R_a}{V_i}. \tag{1.5}$$

The alternating anode current I_a *) flows through the tube and the anode re-

*) Henceforth I_a and V_a symbolise the *alternating* anode current and voltage without direct component.

sistance R_a, and at the anode appears an alternating voltage V_a which is shifted in phase by 180 degrees with respect to I_a and V_i. The alternating anode current caused by V_i is equal to $S \cdot V_i$ according to equ. (1.1); furthermore the alternating anode voltage produces an alternating current V_a/R_i corresponding to equ. (1.2). These currents are additive, so that

$$I_a = S \cdot V_i + \frac{V_a}{R_i}. \qquad (1.6)$$

Now

$$V_a = -I_a \cdot R_a \qquad (1.7)$$

(by reason of the 180° phase shift), so that

$$I_a = S \cdot V_i - \frac{I_a \cdot R_a}{R_i}, \qquad (1.8)$$

and from equation (1.5) the gain is:

$$G = S \cdot \frac{R_i \cdot R_a}{R_i + R_a}. \qquad (1.9)$$

If $R_a \gg R_i$,

$$G = S \cdot R_i = \mu. \qquad (1.10)$$

μ is called the amplification factor of the tube, and represents the theoretical limit of voltage amplification obtainable from the tube. This limit can, however, never be achieved because in practice $R_a/(R_i + R_a)$ is always less than unity.

To obtain a large voltage gain a tube with a high amplification factor, i.e. with high slope and high internal resistance should be chosen. The slope depends almost entirely on the geometry of the electrode system and cannot be increased indefinitely under usual production conditions. The internal resistance, however, can be considerably increased if a second grid, the screen grid, is mounted between the control grid and the anode and is maintained at positive potential. Fig. 1–7 shows the I_a–V_a characteristics of such a tetrode. The flat trend of the curves in the range of higher anode voltages shows that in that region the internal resistance has a considerably higher value than that of the triode as indicated by fig. 1–4.

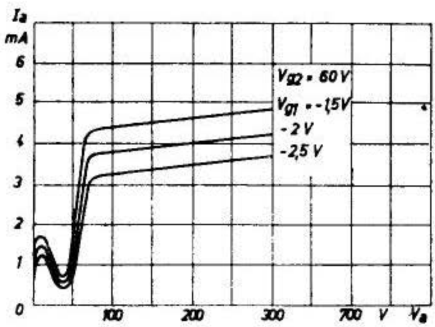


Fig. 1-7. I_a-V_a characteristics of a tetrode.

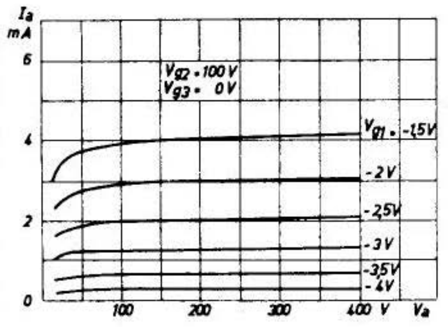


Fig. 1-8. I_a-V_a characteristics of a pentode.

On the left hand side of the diagram the internal resistance becomes negative within a certain range. This is due to secondary emission from the anode. To avoid this effect, a third grid is placed between screen grid and anode, thus forming a pentode. This "suppressor" grid is maintained at cathode potential, thus preventing the secondary electrons from flowing to the screen grid. Fig. 1–8 shows the "I_a–V_a" diagram of a pentode.

As for pentodes $R_i \gg R_a$, equation (1.9) may be simplified to

$$G = S \cdot R_a . \tag{1.11}$$

In fig. 1–9 is shown a typical pentode amplifying tube and the construction of its electrode system.

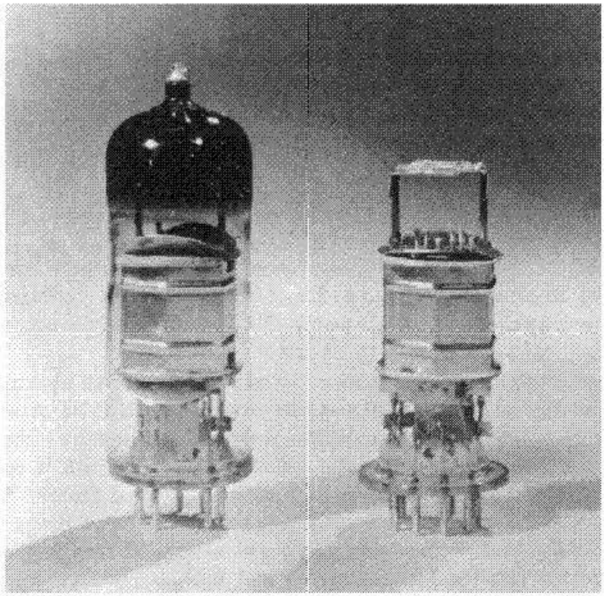


Fig. 1-9. E 80 F pentode amplifying tube. On the right the bulb has been removed to show details of construction.

High vacuum tubes are used in industrial equipment not only for voltage amplification, but also for generating oscillations — often of considerable power output. For this application triodes are generally used or, in special cases, tetrodes. Generation of oscillations is achieved by compensating the attenuation of an oscillatory circuit, tuned to the desired frequency, and connected in the anode circuit of the tube. This so-called tank circuit consists of a capacitor C and an inductor L, furthermore the circuit possesses ohmic resistance R which symbolizes the circuit losses (see fig. 1–10).

Assuming the capacitor is charged with the polarity as shown, it can discharge via R and L, the inductor producing an electromotive force (e.m.f.) which tends to maintain the flowing current. This current then charges the capacitor with reverse polarity and the process repeats *). The current flowing during each discharge of the capacitor produces a voltage drop across the resistance R and the energy dissipated in R "damps" or progessively decreases the amplitude of the oscillations. The larger the resistance R, the faster the oscillations decay. Fig. 1–11 shows such a damped oscillation. The resulting frequency is termed

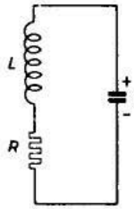


Fig. 1-10. Basic oscillatory circuit.

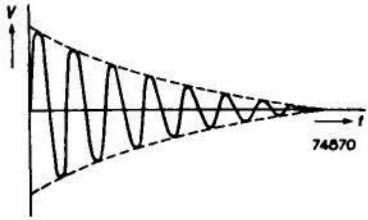


Fig. 1-11. Damped oscillations.

the "resonant frequency" of the oscillatory circuit; it is given by the Thomson formula:

$$\omega_0 = \frac{1}{\sqrt{L \cdot C}}. \tag{1.12}$$

For the sake of simplicity, however, the loss resistance of the circuit has been neglected in this formula. As the influence of this resistance upon the generated frequency is only small, formula (1.12) is sufficiently accurate for most practical cases.

If the voltage drop across R is compensated by applying an alternating voltage of equal amount but of opposite phase, the oscillations will be maintained. This can be done by a circuit such as that shown in fig. 1–12. The tank circuit consisting of L_1 and C_1 is connected in the anode circuit of the tube, and a second coil L_2 is inductively coupled with L_1 and is included in the grid circuit. The magnetic alternating field produced by L_1 induces an alternating voltage in L_2. This voltage controls the grid of the tube, and produces the alternating anode voltage required to compensate the attenuation of the tank circuit.

The tank circuit presents an impedance for the alternating anode current I_a. At resonance (i.e. if the frequency of the alternating current is equal to the resonant frequency of the tank circuit), this external anode load will be

$$R_a = \frac{L}{C \cdot R}. \tag{1.13}$$

It then has the character of an ohmic resistance, i.e. the current and the voltage across it are in phase. For the sake of simplicity this condition will be assumed in the following explanation. A part of the alternating voltage V_a appearing across the external load R_a will be fed back to the grid circuit. This feed-back voltage can be written

$$V_i = -k \cdot V_a. \tag{1.14}$$

*) The oscillatory circuit consisting of capacitance and inductance can be compared with the balance of a watch, C corresponding to the helical spring and L to the flywheel. R is comparable to the friction resistance.

The negative sign is necessary if the oscillations are to be maintained because, as already explained, the phase of the input voltage has to be shifted by 180 degrees with respect to the anode voltage. The feed-back factor k denotes the amount of coupling between anode and grid circuits necessary for maintaining the oscillations. Its value can be calculated from equations (1.6) and (1.7).

Thus

$$k = \frac{1}{S} \cdot \frac{R_i + R_a}{R_i \cdot R_a}, \tag{1.15}$$

or

$$k \cdot S \cdot \frac{R_i \cdot R_a}{R_i + R_a} = 1. \tag{1.16}$$

It is essential that, when the self-excited oscillations start, the left side of equation (1.16) is greater than unity. This is ensured automatically by the fact that, when first switched on, the tube has no negative grid bias, and therefore operates on a part of the I_a–V_g characteristic at which the slope is comparatively high. Due to the occurrence of grid current the capacitor C_g is charged by the positive half cycles of the alternating grid voltage with the polarity shown in fig. 1–12, and will then discharge slowly through the resistor R_g. The voltage drop across this resistor constitutes the negative grid bias of the tube. This bias will increase if the amplitude of the alternating grid voltage increases, and the working point on the I_a–V_g characteristic is therefore shifted into a region of lower slope until equation (1.16) is satisfied, and the alternating grid and anode voltages assume constant values. Usually the working point is then situated so far down in the region of negative grid voltage that only the crests of the positive half cycles of grid voltage drive the grid positive, causing grid current to flow (see fig. 1–13). Similarly, anode current flows only during a part of the positive half cycles of the alternating grid voltage.

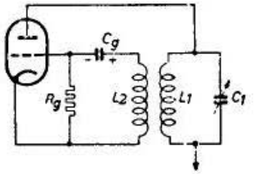


Fig. 1-12. Basic circuit for a tube as oscillator.

This condition is termed "class C operation". It has the advantage of high efficiency and is therefore used in practically all H.F. generating circuits for industrial service.

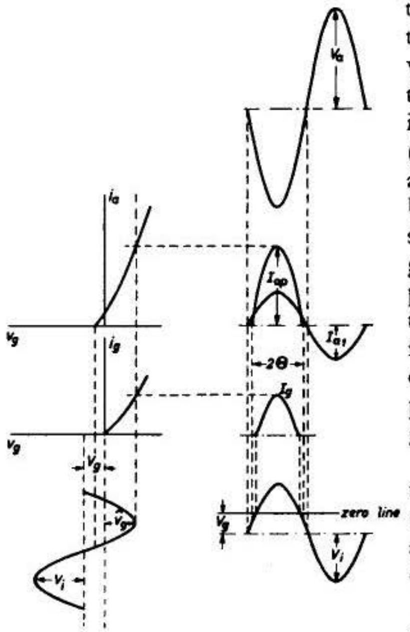


Fig. 1-13. Class C operating condition of a selfexcited tube oscillator.

It should be distinguished from what is termed "class B operation", in which the working point lies approximately at the lower bend of the I_a–V_g characteristic, so that anode current flows during the whole of the positive half cycles of the grid voltage. The efficiency of class B operation is much lower than that of class C, but the generation of harmonics, i.e. the distortion of the amplified voltage caused thereby, is considerably smaller. Class B operation is therefore used in power amplifiers for modulated H.F. (pre-stage modulated radio-transmitters).

The working point of a "class A" amplifier lies on the straight part of the I_a–V_g characteristic. In this case anode current flows during the full cycle of grid voltage. Such amplifiers are used for H.F. or L.F. voltage amplification. In class A operation the amplitude of the grid voltage is usually limited to a value at which grid current does not flow and therefore no driving power is needed.

However, there is no need to employ the comparatively inefficient class A mode in oscillators and power amplifying transmitting circuits, because sufficient driving power for class C or class B operation is always available either by feedback from the tube itself or from a separate driver stage. Transmitting tubes are therefore constructed in such a way that they may be operated at higher grid voltages at which grid current flows.

Operating conditions for transmitting tubes may be well illustrated by V_g–V_a diagrams which are known as "constant current" characteristics, they show the curves of constant anode and grid current for the tube as a function of the grid and anode voltages. An idealized diagram is plotted in fig. 1–14. For the sake of simplicity an ohmic resistance R_a is assumed as the load in the anode circuit of the tube. Across R_a appears a voltage drop corresponding to the value of the anode current I_a. If this current is zero the voltage drop is also zero and the first point of the load line can be plotted on the anode current curve $I_a = 0$ at the anode (supply) voltage V_b. The further points may be constructed according to equation (1.4). To prevent the anode voltage from dropping below the grid voltage, which would give rise to excessive grid currents (see below), the maximum peak anode current is limited by the line $V_a = V_g$. The load line, which is a straight one in this case, will be traversed once in each direction during each cycle of the alternating grid voltage. Point A is the working point of the tube under class A conditions. For every instant the corresponding values of voltages and currents may be taken from the graph; the instantaneous values of grid current and anode current are determined by the intersections of the load line and the curves; the corresponding values of grid voltage and anode voltage can be read off the y- and x-axis of the graph.

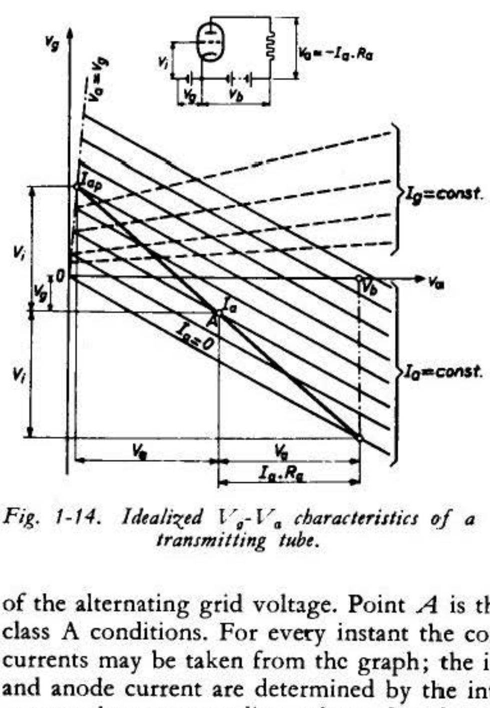


Fig. 1-14. Idealized V_g-V_a characteristics of a transmitting tube.

The conditions under class C operation are shown in fig. 1–15 by the V_g–V_a diagram of the Philips triode transmitting tube TBL 6/6000 (see fig. 1–17). The anode load is formed by a tank circuit tuned to the operating frequency; it therefore represents, at this frequency, an ohmic resistance R_a according to equation (1.13). The load line is therefore again a straight line. In class C operation the working point, A in fig. 1–15, corresponds to such a large value of negative grid voltage V_g that anode current flows during only a part of the positive half cycles of the grid voltage, i.e. from B to C. The anode current impulses during this time contain the fundamental wave of the anode current I_{a1} and a large number of harmonics. The angular duration of anode current flow Θ, which corresponds to half the time during which current flows, measured in degrees, can be ascertained easily from the diagram. It would obviously be 90 degrees if current flowed during the complete half of the load line AC. As, however, current flows only during the part BC,

$$\cos \Theta = \frac{AB}{AC} = \frac{DE}{DF}. \qquad (1.17)$$

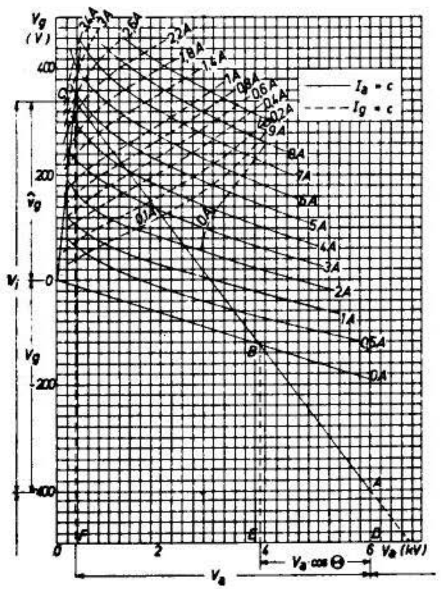


Fig. 1-15. Constant current characteristics o the Philips TBL 6/6000 transmitting triode with load line.

In the case of fig. 1–15, Θ is 67 degrees.

From Θ and the anode peak current I_{ap} the amplitude of the fundamental current wave I_{a1} can be determined. Normally,

$$I_{a1} = I_{ap} \cdot f_1(\Theta). \qquad (1.18)$$

In the case of a tube with an idealized linear I_a–V_g characteristic (this simplifying assumption can be made in most cases) Fourier analysis of the anode current impulses gives:

$$f_1(\Theta) = \frac{\Theta - \frac{1}{2} \cdot \sin 2\Theta}{\pi\,(1 - \cos \Theta)}. \qquad (1.19)$$

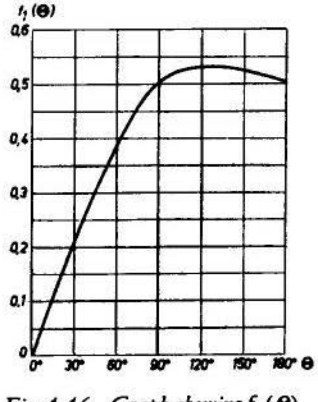


Fig. 1-16. Graph showing $f_1(\Theta)$ as a function of Θ.

This function is plotted in the graph of fig. 1–16.

The alternating anode voltage V_a may be taken easily from the diagram fig. 1–15; in this case it will be nearly 5.6 kV. With $f_1(\Theta) = 0.42$ and $I_{ap} = 4.8$ A, $I_{a1} = 2$ A. The output power of the tube

$$W_o = \frac{I_{a1}\,V_a}{2}, \qquad (1.20)$$

which in the case considered gives 5.6 kW approximately.

The grid direct current I_g can be determined

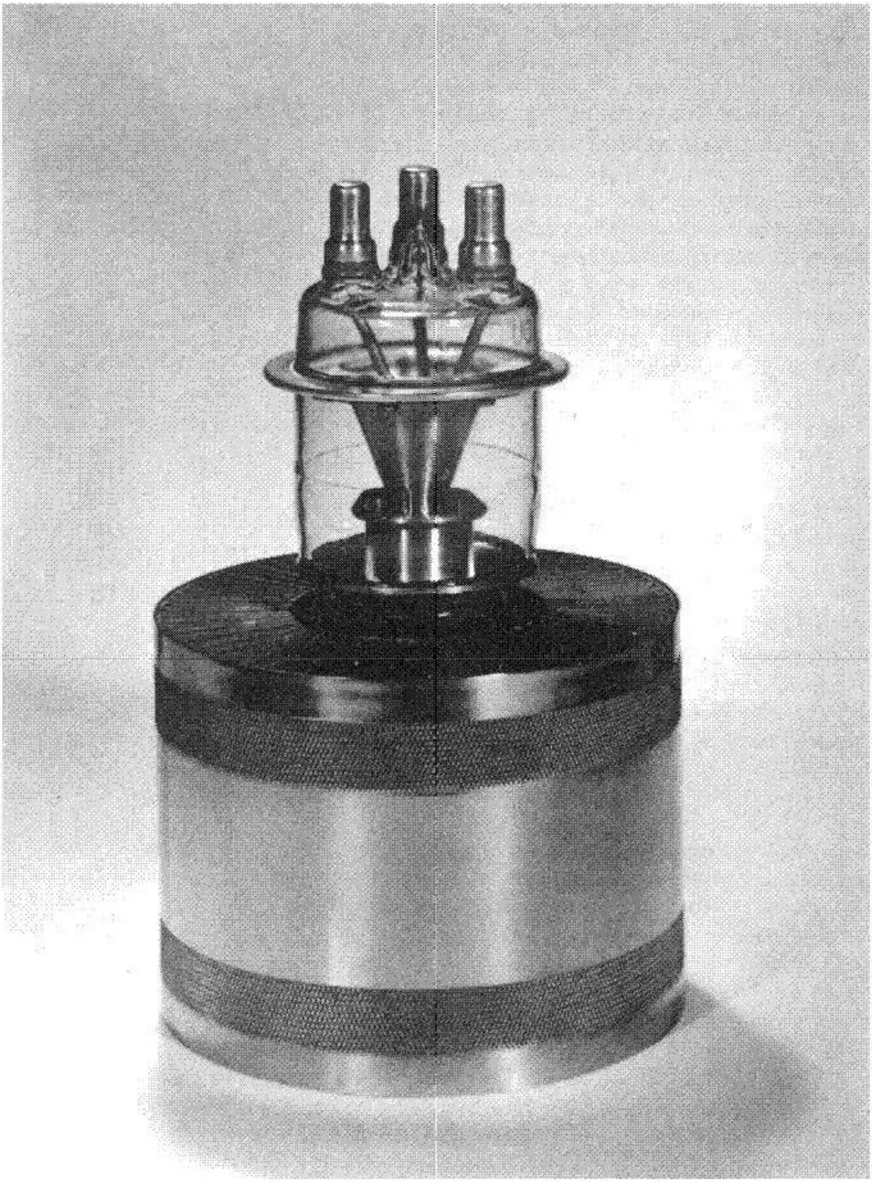


Fig. 1-17. Philips transmitting triode TBL 6/6000.

by integrating the grid current curve which can be constructed from the instantaneous values of i_g derived from the graph:

$$I_g = \frac{1}{2\pi} \cdot \int_0^{2\pi} i_g \cdot d\varphi. \qquad (1\,21)$$

Similarly the necessary input power will be

$$W_{ig} = \frac{1}{2\pi} \cdot \int_0^{2\pi} i_g v_g \cdot d\varphi \approx 0.9\ V_s I_g, \qquad (1.22)$$

where v_g denotes the instantaneous value of the alternating grid voltage.

When an electrode, anode or grid, is positive with respect to the cathode, the possibility of current flowing to this electrode exists. When electrons strike the electrode they release their kinetic energy in the form of heat. This heat thus generated is called the power dissipation and must be removed to avoid overheating and finally destruction of the tube. This can be done in several ways. Small tubes can be cooled sufficiently by natural heat radiation which may be facilitated by giving the electrode a suitable form and surface. To dissipate larger quantities of heat this form of cooling does not suffice, and forced cooling by water or air must be used. For this reason large transmitting tubes are often so constructed that the anode, which has the largest dissipation, forms a part of the vacuum-tight envelope of the tube. On the external side of the anode a cooling radiator may be mounted. Fig. 1–17 shows a commercial air-cooled transmitting triode with external anode for industrial service (Philips TBL 6/6000).

For every tube the maximum ratings of anode and grid dissipation are published by tube manufacturers. These ratings should never be exceeded; otherwise the life of the tube will be greatly reduced. The danger of overloading occurs, for example, with transmitting tubes operating in industrial H.F. generators if the load varies greatly, i.e. if the generator is operated under no-load condition or short-circuited. In the latter case the resistance of the tank circuit becomes very small and the efficiency of the tube decreases until oscillations are no longer maintained. Consequently the anode dissipation increases to a point at which the maximum rating may be exceeded. On the other hand, under no-load conditions the anode impedance will rise considerably, and in consequence the amplitude of alternating anode voltage also increases. Due to feed-back, the alternating grid voltage rises and grid current may exceed the limiting value. This effect will be aggravated by the fact that grid and anode voltages are out of phase by 180 degrees, so that the anode may be at a lower potential than the grid during the positive half cycles of grid voltage. The grid current may then increase until the grid wires melt and the tube is destroyed.

Even if, as in modern industrial H.F.-equipment, fuses and protection circuits are included to switch off the generator in case of overloading, it is recommended that the above possibilities are kept in mind when operating a generator under severe conditions.

Estimation of the grid loading is comparatively simple. Obviously the grid dissipation is equal to the difference between the H.F. driving power and the power losses in the grid voltage source or the grid resistor. Thus:

$$W_g = W_{ig} - I_g V_g, \qquad (1.23)$$

I_g being the d.c. grid current and V_g the grid biasing voltage.

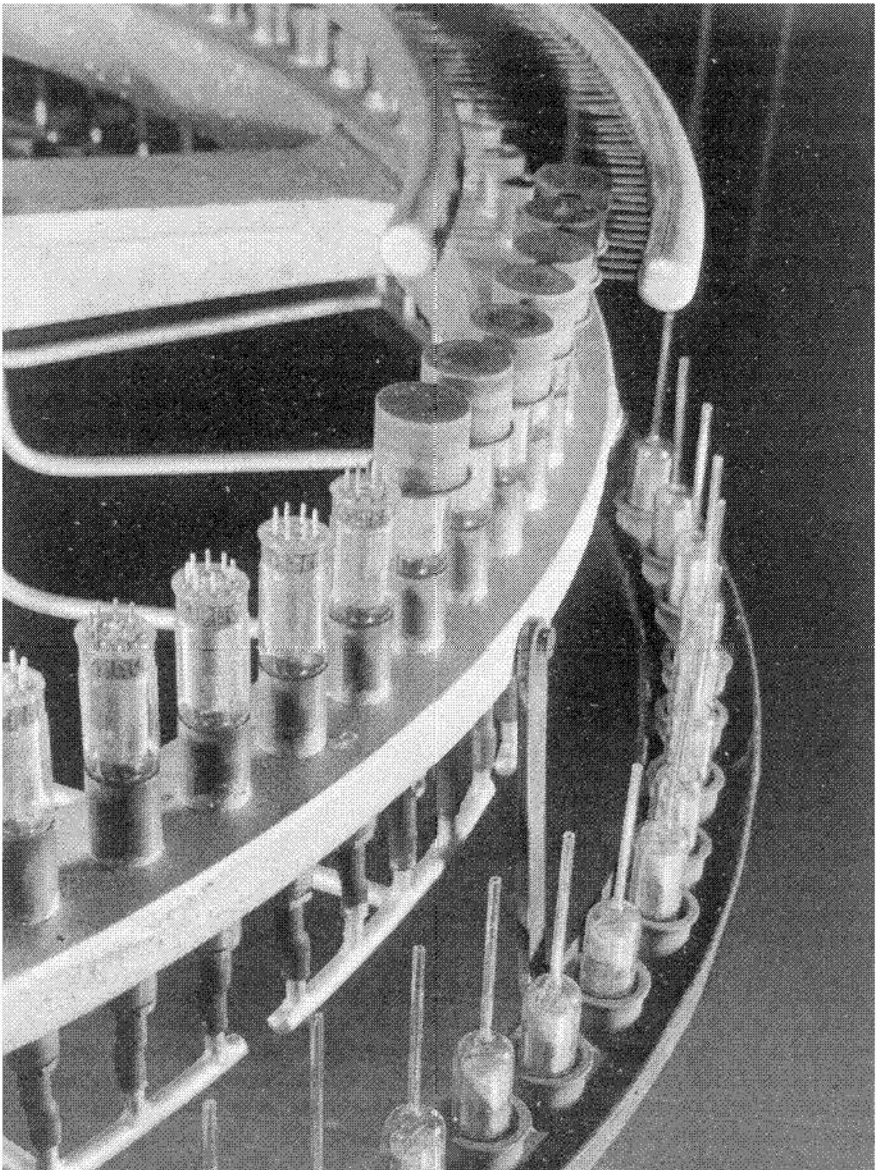


Fig. 1-18. Automatic sealing of miniature amplifying tubes.

From equation (1.22)

$$W_g = I_g \,(0.9\, V_i - V_g) \approx I_g \cdot \hat{v}_g, \tag{1.24}$$

where $\hat{v}_g$ denotes the peak value of positive grid voltage (see fig. 1–15).

The cathode heating supply for tubes in industrial apparatus is usually provided by a transformer from the a.c. mains. Maximum and minimum values of heater voltage are usually published by tube manufacturers; in the interest of long useful tube life they should not be exceeded. In many cases these tolerances are so large that normal fluctuations of the mains voltage may be disregarded. Where this is not the case voltage stabilizing devices should be provided in order to reduce the fluctuations to a permissible level.

Sometimes a hand-operated adjustable resistor or variable-core transformer with voltmeter etc. will suffice for heater regulation, but in this case careful and continuous supervision is necessary in order to maintain the nominal values of heating power.

Fig. 1–18 is a picture of an automatic machine employed in the manufacture of amplifying tubes, and shows the automatic sealing of miniature tubes.

2. RECTIFYING TUBES

Rectifying tubes are diodes or two-electrode tubes, containing only a directly or indirectly heated cathode and one or more anodes. In industrial equipment such tubes are mostly used for changing the alternating voltage and current delivered by the mains into d.c. power.

Rectifying tubes are either highly evacuated or gas-filled. Vacuum tubes are used for the rectification of comparatively small powers; they are found chiefly in single- or two-phase circuits.

In fig. 2–1 the conventional symbols for a two-anode, directly heated tube and a single-anode indirectly heated tube are shown. The gas filling is indicated by a spot beside the cathode *).

Fig. 2.1. Tube symbols (left: two-anode directly heated gas-filled rectifying tube, right: single-anode indirectly heated gas-filled tube).

The basic circuit of a single-phase rectifier using a single-anode tube is shown in fig. 2–2. The secondary of transformer Tr produces an alternating voltage V_{tr} which is applied to the rectifying tube in series with the reservoir capacitor C across which the rectified voltage appears. The current can pass only in one direction as the negative electrons can flow only from the cathode to the anode when the anode potential is positive. This is the case only during one half of each cycle of the alternating voltage (half-wave rectification); during these periods the capacitor is charged with the polarity shown in fig. 2–2. In the following half cycle no current can flow and the capacitor will be discharged partially during this period by the load resistance R (for the sake of simplicity an ohmic resistance is assumed). In the following positive half cycle the process is repeated.

*) Instead of marking the tube symbols by a spot, they are often hatched to indicate the gas filling.

In fig. 2–3 this voltage variation is shown as a function of time. Obviously the voltage across the capacitor is opposed to the positive half cycles of the voltage delivered by the transformer, so that charging current can flow only

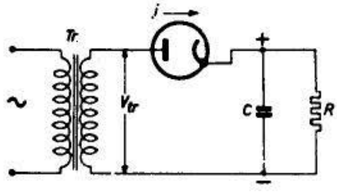


Fig. 2.2. Basic circuit of a single-phase half-wave rectifier.

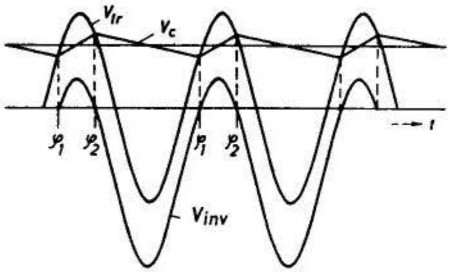


Fig. 2-3. Output voltage of a single-phase half-wave rectifier.

during the time $\varphi_2 - \varphi_1$ when the transformer voltage is predominant. During the negative half cycles, however, the voltage across the capacitor is added to the transformer voltage; in this period, therefore, a considerably higher "inverse voltage" is applied to the tube.

The rectified output voltage is not constant but has superimposed on it an alternating voltage having a frequency equal to that of the mains. This "ripple" voltage may be undesirable in the load circuit and should therefore be suppressed as far as possible. It is obvious that the ripple voltage will be smaller if the reservoir capacitor is chosen larger or if the load current is smaller. Moreover a considerable reduction of the ripple voltage can be obtained if a smoothing filter is added consisting of a choke (inductance) and a smoothing capacitor (fig. 2–4). Assuming a sinusoidal ripple voltage, the amount of smoothing, i.e. the ratio of the ripple voltage amplitudes following and preceding the filter will be

$$\frac{V_2}{V_1} = \frac{1}{\omega^2 LC_2 - 1}. \tag{2.1}$$

Two single-anode rectifying tubes can be connected in such a way that the

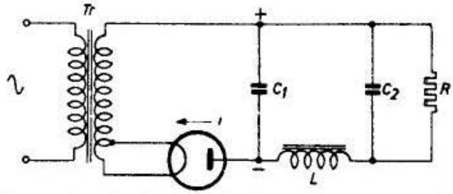


Fig. 2-4. Single-phase half-wave rectifier with smoothingfilter.

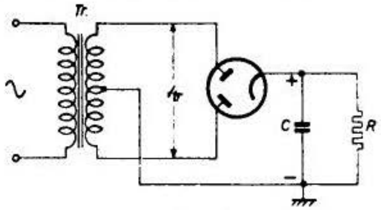


Fig. 2-5. Two-phase half-wave rectifier circuit.

reservoir capacitor will be charged by both half cycles. In that case it is often convenient to use tubes containing two anodes and a common cathode. Fig. 2–5 shows the basic circuit of a two-phase half-wave rectifier *) incorporating

*) This circuit is often called a "full-wave rectifier" in literature, but to avoid confusion, preference is given to the term "two-phase half-wave rectifier", the rectifier being fed by an alternating voltage having two opposite phases to which half-wave rectification is applied. The term "full-wave rectification" will be reserved for bridge circuits, which are discussed later.

such a two-anode tube; the single-phase mains voltage is converted into two voltages which are in antiphase.

Fig. 2-6 indicates the voltage waveform across the capacitor in this circuit. Obviously the ripple voltage now has twice the frequency of the mains, and therefore, as can be shown from equation (2.1), a given filter will give four times the smoothing in a two-phase circuit compared with a single-phase circuit. Moreover, the ripple voltage percentage is smaller than in a single-phase rectifier because the discharge times of the capacitor are much shorter. Also the peak current drawn from the cathode is smaller because the current flow is distributed over the whole cycle. For these reasons two-phase rectifying circuits are generally used when high vacuum tubes are employed. A commercial type of two-anode rectifying tube for two-phase rectification is illustrated in fig. 2–7.

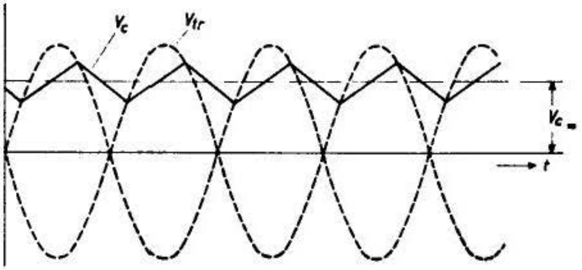


Fig. 2-6. Output voltage of a two-phase half-wave rectifier.

In contrast to high vacuum rectifiers, there are the gas-filled rectifying tubes which are widely used in industrial electronics. Like vacuum tubes, they have a directly or indirectly heated oxide-coated cathode and one or more anodes, but the envelope is filled with one of the inert gases argon, xenon or helium at low pressure, or with mercury vapour or with a mixture of both.

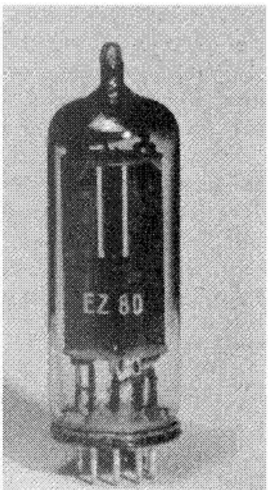


Fig. 2-7. Two-anode rectifying tube type EZ 80.

If a positive potential of only a few volts is applied to the anode of such a tube only a very small current will flow. If the anode voltage is increased beyond a certain value termed the "ignition voltage", V_{ign}, the tube suddenly fires and the anode current rises to a value which may be considerably higher than that in a vacuum tube of comparable size. This effect is caused by the ionisation of the gas atoms; at the ignition voltage the electrons achieve such a high speed that, when colliding with the gas atoms, they eject other electrons from the atoms, leaving the gas in the form of positive ions. The newly produced electrons are attracted to the anode, thereby increasing the anode current, and the positive ions move towards the cathode, where they neutralize the "space charge" or cloud of electrons which exists in the region of the cathode and limits the number of electrons which can leave the cathode. Due to this neutralizing action the anode current is further increased.

When this condition is reached the value of the anode current is determined almost entirely by the values of the anode voltage and the external resistance in the anode circuit. The voltage drop across the tube itself, i.e. the so-called "arc voltage", V_{arc}, arises mainly in the vicinity of the cathode, and is practically independent of the value of the anode current. Its value depends upon various factors, but mainly on the gas used for the filling and its pressure. The gas pressure in the case of a mercury-vapour tube is greatly dependent upon the temperature, so in these tubes the arc voltage is influenced by the working temperature. The arc voltage ranges from 8 to 32 volts according to the type of gas-filling; mercury-vapour filled tubes have an arc voltage of approximately 16 volts. It will thus be seen that the losses generated in the tube, i.e. the product of arc voltage and average anode current are comparatively small, and the higher the anode voltage the lower will be the percentage loss.

If the effective anode voltage becomes smaller than the arc voltage, the discharge is extinguished and the flow of anode current ceases. This occurs, for example, if the external anode circuit is interrupted.

Rectifying circuits using gas-filled tubes do not greatly differ from those for high-vacuum tubes except that the reservoir capacitor should be omitted. This is necessary because owing to the very small internal resistance of the gas-filled tube, such high peak currents would flow while the capacitor is charged that the cathode would be seriously damaged. The smoothing filter circuit will therefore commence with a choke.

In the remainder of this chapter some factors which are of importance in the design of rectifiers employing gas-filled tubes will be dealt with. The simplest circuit is the single-phase, half-wave rectifier shown in fig. 2–8, from which the multi-phase and full-wave rectifying circuits illustrated in fig. 2–16 can be comparatively easily derived.

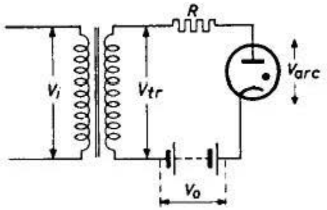


Fig. 2-8. Simple single-phase half-wave rectifier circuit with gas-filled tube and counter e.m.f.

It can be imagined that a counter-electromotive force V_o is inserted in the circuit, and is independent of the value of the current flowing (this is the case for instance when batteries are charged by the rectifier). The load is symbolized by an ohmic resistance R which also includes the resistance of the transformer winding. If V_{ign} is the ignition voltage, it is obvious that ignition will occur only if

$$\sqrt{2}\, V_{tr} > V_{ign} + V_o,$$

i.e. if

$$\frac{\sqrt{2}\, V_{tr}}{V_{ign} + V_o} = k > 1. \qquad (2.2)$$

It is reasonable to choose V_{tr} so that the value of k is between 1,15 and 1,2 to ensure that ignition of the tube will occur with certainty even where the mains voltage is subject to fluctuation. The tube having ignited, the voltage across the tube decreases to the arc voltage V_{arc}. The instantaneous value of the current flowing then is

$$i = \frac{\sqrt{2}\, V_{tr} \cdot \sin\varphi - V_{arc} - V_o}{R}. \qquad (2.3)$$

Making use of the concepts of firing angle φ_1 and extinguishing angle φ_2 of the tube (see fig. 2-9), the mean anode current per phase I_o is obtained by integrating the current from φ_1 to φ_2 and dividing by the whole cycle 2π:

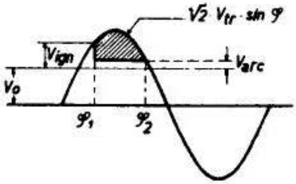


Fig. 2-9. Voltage curve of a rectifier according to fig. 2-8.

$$I_o = \frac{1}{2\pi} \cdot \int_{\varphi_1}^{\varphi_2} i \cdot \mathrm{d}\varphi =$$

$$= \frac{1}{2\pi R} \cdot \int_{\varphi_1}^{\varphi_2} (\sqrt{2}\, V_{tr} \cdot \sin\varphi - V_{\mathrm{arc}} - V_o) \cdot \mathrm{d}\varphi. \quad (2.4)$$

If a denotes the voltage ratio $(V_{\mathrm{arc}} + V_o)/\sqrt{2}\, V_{tr}$ (a obviously always being less than unity), equation (2.4) becomes:

$$I_o = \frac{\sqrt{2}\, V_{tr}}{2\pi R} \cdot \int_{\varphi_1}^{\varphi_2} (\sin\varphi - a) \cdot \mathrm{d}\varphi. \quad (2.5)$$

The following approximations are admissible (see fig. 2-9):

$$\left.\begin{aligned} \varphi_1 &= \sin^{-1} a, \\ \varphi_2 &= \pi - \sin^{-1} a. \end{aligned}\right\} \quad (2.6)$$

If the integration is carried out, it will be found that the mean current per phase is:

$$I_o = \frac{\sqrt{2}\, V_{tr}}{\pi R} (\sqrt{1 - a^2} - a \cdot \cos^{-1} a), \quad (2.7)$$

or

$$I_o = \frac{\sqrt{2}\, V_{tr}}{\pi R} \cdot Q. \quad (2.8)$$

In fig. 2-10 Q is plotted as a function of a. The maximum permissible mean current of the tube is specified in the published data; it can be shown from equ. (2.8) that the total resistance of the rectifying circuit must be

$$R \geqq \frac{\sqrt{2}}{\pi} \frac{V_{tr}}{I_c} \cdot Q. \quad (2.9)$$

When designing a rectifier, therefore, resistors R_a should be inserted in the anode leads in order to limit the current. The values of these resistors can be determined from equation (2.9) after deducting the transformer and load resistances.

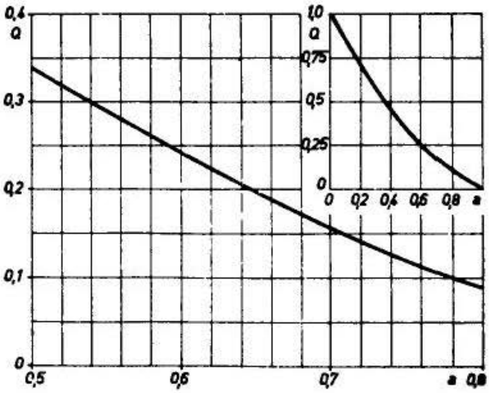


Fig. 2-10. Graph showing Q as a function of a.

The peak value of the current

$$i = \frac{\sqrt{2}\, V_{tr}\,(\sin\varphi - a)}{R}$$

obviously occurs at $\varphi = 90°$, and is

$$\hat{\imath} = \frac{\sqrt{2}\, V_{tr}\,(1 - a)}{R}, \tag{2.10}$$

so that

$$\frac{\hat{\imath}}{I_o} = \frac{(1 - a)\,\pi}{Q}. \tag{2.11}$$

When using a rectifier tube of a given type it is necessary to check that the maximum permissible peak anode current as calculated from equations (2.10) and (2.11) is not exceeded under working conditions.

In many cases the load of a rectifier is inductive. If the ohmic resistance of the rectifier circuit is then neglected the basic circuit will be as fig. 2–11 and the following equation applies:

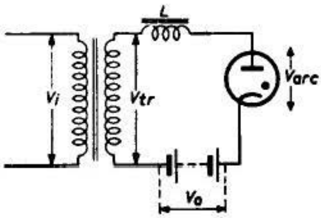


Fig. 2-11. Single-phase half-wave rectifier with inductive load and counter e.m.f.

$$L \cdot \frac{di}{dt} = \sqrt{2}\, V_{tr} \cdot \sin\omega t - V_{\text{arc}} - V_o, \tag{2.12}$$

from which

$$i = \frac{1}{L}\int_{t_1}^{t} (\sqrt{2}\, V_{tr} \cdot \sin\omega t - V_{\text{arc}} - V_o) \cdot dt, \tag{2.13}$$

or

$$i = \frac{1}{\omega L}\int_{\omega t_1}^{\omega t} (\sqrt{2}\, V_{tr} \cdot \sin\omega t - V_{\text{arc}} - V_o) \cdot d\omega t. \tag{2.14}$$

From equation (2.12) it follows that the maximum of current, which occurs at $di/dt = 0$, is reached at a point at which:

$$\sqrt{2}\, V_{tr} \cdot \sin\omega t = V_{\text{arc}} + V_o.$$

This means that there is a phase difference between voltage and current as is shown in fig. 2–12. Moreover it follows from equation (2.14) that $i = 0$ if the integral becomes zero, i.e. if the two shaded areas above and below the horizontal line $V_{\text{arc}} + V_o$ in fig. 2–12 are equal. Curve *b* shows the voltage V_L appearing across the inductance L, and curve *c* shows the anode current i.

It is to be seen that the current is maintained beyond the instant at which the transformer voltage V_{tr} has passed the zero line and has become negative. This may be strange at first sight because, as has already been stated, a gas-filled tube ceases to conduct when the anode voltage falls below the value of the arc voltage. However, the inductance L produces a voltage tending to maintain the current flow, and this voltage is sufficient to keep the anode of the tube positive with respect to the cathode by an amount equal to the arc voltage. Thus the current continues to flow until the energy stored in the inductance has discharged, when the voltage collapses and the current ceases. This, as already stated, occurs when the shaded areas in fig. 2-12 are equal. However, if an additional ohmic resistance R is present in the circuit (this will always be so in practice) the current flow ceases somewhat earlier. The difference in the two shaded areas is then determined by the voltage drop across the resistance R caused by the current flow.

Equation (2.14) can be written

$$i = \frac{\sqrt{2}\, V_{tr}}{\omega L} \cdot \int_{\omega t_1}^{\omega t} (\sin \omega t - a) \cdot d\omega t, \quad (2.15)$$

whence

$$i = \frac{\sqrt{2}\, V_{tr}}{\omega L} \cdot \left\{ \cos \omega t_1 - \cos \omega t - a\,(\omega t - \omega t_1) \right\}. \quad (2.16)$$

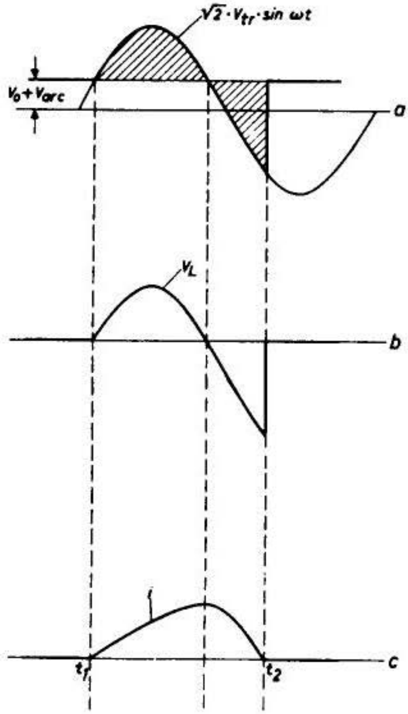


Fig. 2-12. Voltage and current curves of a rectifier according to fig. 2-11.

Considering $\omega t_1 = \sin^{-1} a$, and introducing the conducting time

$$\tau = \omega t - \omega t_1:$$

$$i = \frac{\sqrt{2}\, V_{tr}}{\omega L} \left\{ \sqrt{1 - a^2}\,(1 - \cos \tau) + a \cdot \sin \tau - a\tau \right\}. \quad (2.17)$$

It has already been stated that the conducting time of the tube is considerably extended by the inductance. This can easily be shown mathematically if the

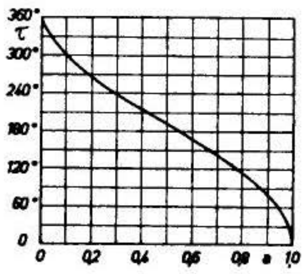


Fig. 2-13. Conducting time τ as a function of a.

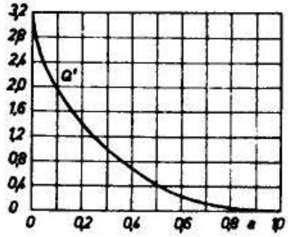


Fig. 2-14. Graph showing Q' as a function of a.

angle at which the current reaches its peak value is determined. This can be done by putting equation (2.12) equal to zero:

$$\omega t_{(i=\max)} = \pi - \sin^{-1} a. \tag{2.18}$$

The current reaches its peak value at a point where it would have already become zero if the load had been purely resistive. The actual conducting time τ can be calculated by putting equation (2.17) equal to zero; it is a function of a (see fig. 2–13).

The peak value of the current, $\hat{\imath}$, can be determined easily from equation (2.16) and is:

$$\hat{\imath} = \frac{2\sqrt{2}\, V_{tr}}{\omega L} \left(\sqrt{1-a^2} - a \cdot \cos^{-1} a\right) = \frac{2\sqrt{2}\, V_{tr}}{\omega L} \cdot Q. \tag{2.19}$$

Furthermore, the mean anode current I_o can be calculated from equation (2.14); i.e.:

$$I_o = \frac{\sqrt{2}\, V_{tr}}{\pi \omega L} \cdot Q', \tag{2.20}$$

Q' being another function of a which is plotted in fig. 2–14.

A matter of great importance is the average rectified direct voltage V_o which can be obtained from an m-phase rectifier if the r.m.s. transformer voltage per phase is V_{tr}. Because the m phases are equivalent, each phase contributes to the output voltage during the time interval $2\pi/m$, as is shown in fig. 2–15. On this assumption it may be written:

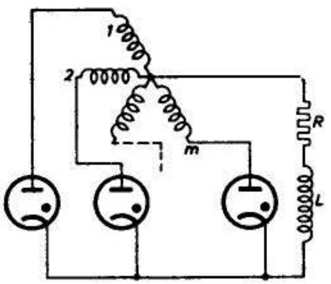
$$V_o = \frac{m}{2\pi} \cdot \int_{\frac{\pi}{2}-\frac{\pi}{m}}^{\frac{\pi}{2}+\frac{\pi}{m}} \sqrt{2}\, V_{tr} \cdot \sin\varphi \cdot d\varphi; \tag{2.21}$$

integrating across the interval $2\pi/m$ gives:

$$V_o = \sqrt{2} \cdot \frac{m}{\pi} \cdot \sin\frac{\pi}{m} \cdot V_{tr} = M\, V_{tr}. \tag{2.22}$$

The term

$$M = \sqrt{2}\, \frac{m}{\pi} \cdot \sin\frac{\pi}{m} \tag{2.23}$$



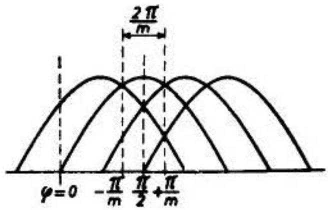


Fig. 2-15. Voltage curves of an m-phase rectifier.

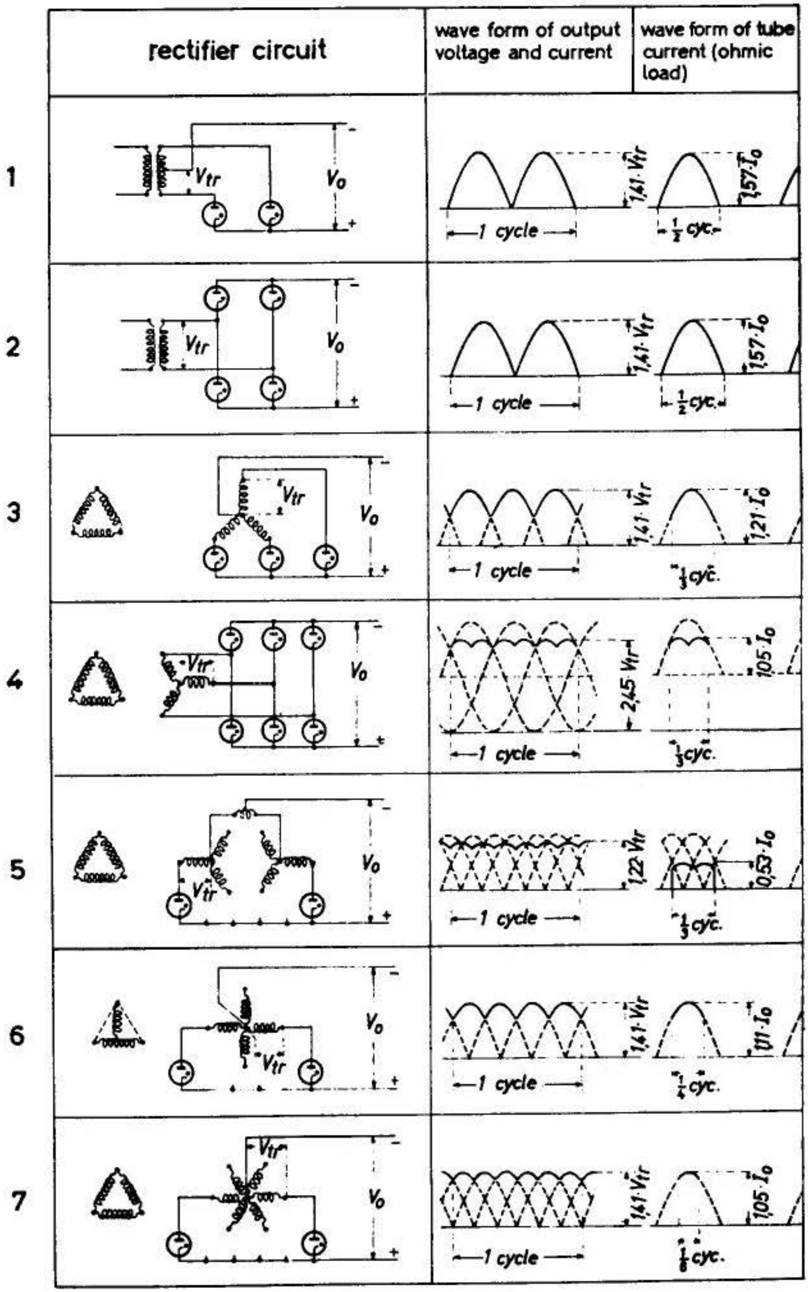


Fig. 2-16. Some typical rectifier circuits.

is called the phase factor. In the following table the values of M are indicated for several values of m:

m	2	3	4	6	12	18	...	∞
M	0.900	1.170	1.273	1.350	1.398	1.407		$\sqrt{2}$
$\frac{1}{M}$	1.111	0.855	0.786	0.741	0.715	0.711		0.707

In equation (2.22), however, the voltage losses arising in the transformer windings and across the rectifying tubes are neglected.

The most common rectifying circuits are shown in fig. 2–16. The following table gives values for the output voltages and currents in terms of the tube voltages and currents which may be used in approximate calculations.

V_{tr} is the transformer voltage per phase (r.m.s. value) and I_a the mean current per anode. The table indicates the theoretical values, transformer reactances being neglected; in practice the voltage losses in the transformer and across the tubes should be taken into account. Moreover, a certain voltage loss arises during the commutation period, the time required for the current to be taken over from one anode to the next. Generally, the over-all voltage losses caused by these factors at full load are approximately 10 to 15 per cent of the output voltage.

Circuit No.	Rectifying circuit	Mean output voltage V_o	Mean output current I_o	Inverse voltage (peak) per tube V_{inv}
1	two-phase half-wave	$0.318\ V_{inv}$ $0.900\ V_{tr}$	$2\ I_a$	$2.828\ V_{tr}$ $3.142\ V_o$
2	two-phase full-wave (bridge)	$0.636\ V_{inv}$ $0.900\ V_{tr}$	$2\ I_a$	$1.414\ V_{tr}$ $1.571\ V_o$
3	three-phase half-wave	$0.478\ V_{inv}$ $1.170\ V_{tr}$	$3\ I_a$	$2.450\ V_{tr}$ $2.094\ V_o$
4	three-phase full-wave (bridge)	$0.956\ V_{inv}$ $2.340\ V_{tr}$	$3\ I_a$	$2.450\ V_{tr}$ $1.047\ V_o$
5	three-phase half-wave (double Y)	$0.478\ V_{inv}$ $1.170\ V_{tr}$	$6\ I_a$	$2.450\ V_{tr}$ $2.094\ V_o$
6	four-phase half-wave	$0.450\ V_{inv}$ $1.273\ V_{tr}$	$4\ I_a$	$2.828\ V_{tr}$ $2.221\ V_o$
7	six-phase half-wave	$0.478\ V_{inv}$ $1.350\ V_{tr}$	$6\ I_a$	$2.828\ V_{tr}$ $2.094\ V_o$

For even values of m the maximum value of the inverse voltage per tube can be calculated from the formula:

$$V_{inv} = 2\sqrt{2}\ V_{tr} = 2{,}828\ V_{tr}. \qquad (2.24)$$

For three-phase circuits:

$$V_{\text{inv}} = \sqrt{3} \cdot \sqrt{2}\, V_{tr} = 2{,}450\, V_{tr}. \tag{2.25}$$

The inverse voltage as a function of the mean rectified output voltage V_o for even values of m is given according to equation (2.22) by:

$$V_{\text{inv}} = \frac{2}{\frac{m}{\pi} \cdot \sin \frac{\pi}{m}} \cdot V_o, \tag{2.26}$$

and for three-phase circuits by:

$$V_{\text{inv}} = \frac{\sqrt{3}}{\frac{3}{\pi} \cdot \sin \frac{\pi}{3}} \cdot V_o = \tfrac{2}{3}\pi\, V_o. \tag{2.27}$$

For full-wave (bridge) circuits the inverse voltage per tube is only half of these values, so that the values given by equations (2.26) and (2.27) should be divided by 2.

The life to be expected from gas-filled tubes is generally very high. Two circumstances may influence life: bombardment of the cathode by positive ions and the gas "clean-up". The components of the tube assembly tend to absorb gas atoms during life. For instance in rectifying circuits the anode attains a high negative potential during the inverse period, so that gas ions may reach the anode with a high speed and partially penetrate it. Due to the slowly decreasing gas pressure in the tube the electrical data ultimately change so greatly that the tube must be replaced. However, gas clean-up is of importance only in inert gas-filled tubes because mercury-vapour filled tubes contain excess mercury in liquid form which maintains the pressure during the life of the tube. This is one of the reasons why mercury-vapour filled tubes are usually preferred for use in industrial equipment.

Bombardment of the cathode by positive ions occurs when the tube is conducting and increases as the anode current and thus the gas ionisation increases. As the cathode can be ultimately destroyed by continuous heavy ion bombardment, the maximum per-

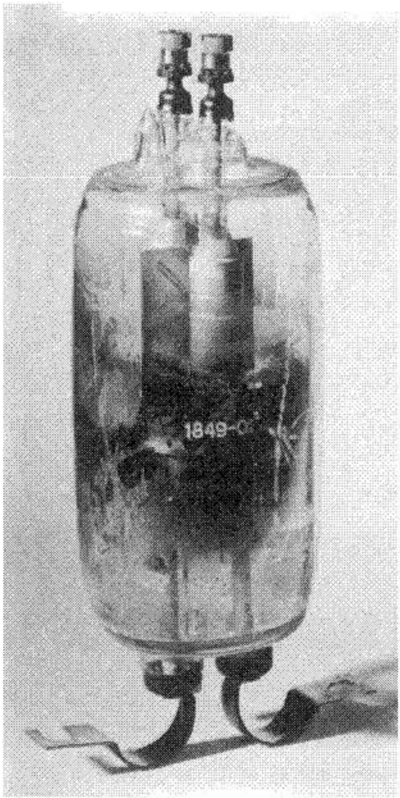


Fig. 2-17. Long-life rectifying tube, Philips Type 1849.

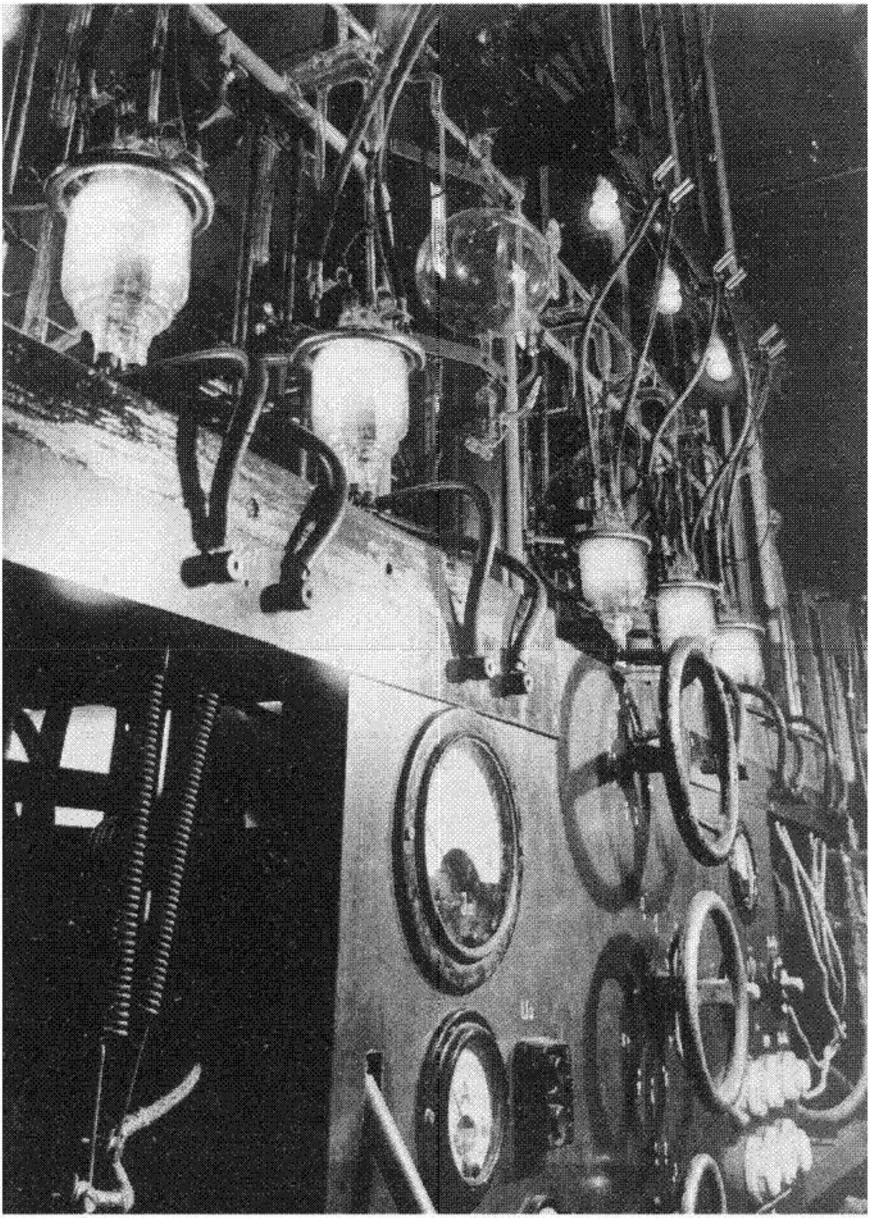


Fig. 2-18. Gas-filled rectifying tubes in course of manufacture.

missible value of the mean anode current and the peak anode current specified by the tube manufacturers should never be exceeded. By special constructional measures inside the tube, particularly by good screening of the cathode, ionic bombardment under normal working conditions can be kept very low. For instance, the two-anode rectifying tube shown in fig. 2–17, which is designed for a mean anode current of 25 amperes, attains a useful life of 20 000 to 30 000 hours.

If mercury-vapour filled tubes have been in stock for a considerable time, or have been exposed to heavy mechanical shocks (for instance during transportation etc.), it may happen that some of the liquid mercury inside the tube has splashed on the anode or other parts of the electrode system. If the tubes were immediately put into service in this condition there would be a risk of arc-back, i.e. a current flow in reverse direction. To avoid this, it is recommended that the cathodes of the tubes should be run at working temperature for a short length of time without applying anode voltage before the tubes are put into operation, thus allowing all mercury to evaporate from the anode and condense in the lower, cooler part of the tube. Recommendations on these lines will usually be given by tube manufacturers; they should be observed carefully in order to ensure a long useful tube life.

Fig. 2–18 shows gas-filled rectifying tubes in course of manufacture.

3. THYRATRONS

A thyratron is a gas-filled discharge tube containing a heated cathode, one or more grids and an anode. The influence of the grid gives the thyratron characteristics very different from those of the gas-filled rectifying tubes described in the preceding chapter, and makes it one of the most important components of industrial electronic apparatus. If a sufficiently great negative voltage is applied to the grid of a thyratron, a positive voltage being applied via a resistor to the anode (fig. 3–1), practically no anode current flows and the tube remains cut off, even though the anode voltage may be several hundred volts or more. If the negative grid bias is now progressively reduced, a point is reached at which the tube fires instantaneously and a large anode current flows, the value of which is dependent on the anode resistance and the applied anode voltage. The thyratron then behaves just like a gas-filled rectifying tube without grid.

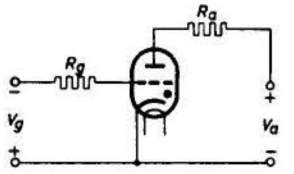


Fig. 3-1. Basic thyratron circuit.

For each value of positive anode voltage there is a corresponding value of negative grid voltage at which firing of the tube occurs. This connection between anode voltage and grid ignition voltage is usually plotted in a graph, termed the critical control characteristic of the tube. There are tubes with negative, positive or transition control characteristics, according to the values of grid voltage required for igniting.

Fig. 3–2 shows the three possibilities for mercury-vapour filled tubes. Under conditions corresponding to the region to the left side of the characteristics the tubes remain non-conducting; on the right-hand side ignition will occur.

It must be understood, however, that a tube, once ignited, cannot be cut off by increasing the negative grid voltage as in the case of high vacuum tubes where the anode current may be continuously controlled by the negative grid voltage. In the thyratron a sheath of positive gas ions screens the grid so that it can no longer exercise control. The anode current therefore continues to

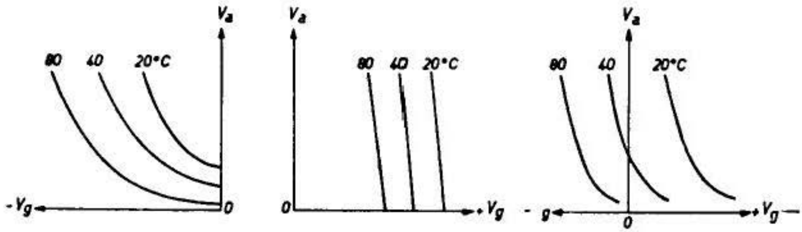


Fig. 3-2. Control characteristics of mercury-vapour filled thyratrons.

flow until the voltage between anode and cathode is reduced below the arc voltage value *).

If it is desired that the tube should remain non-conducting after the discharge has been interrupted, the anode voltage should not be allowed to reach its full value until after a certain short time interval has elapsed. This interval is the "de-ionisation time", i.e. the time needed for the grid to regain control of the tube; it is in the order of microseconds and commences at the moment when the anode current ceases. As the de-ionisation time depends on the intensity of ionisation, and this is again a function of the value of the anode current; it is specified for a given maximum mean anode current and a condensed mercury temperature of 40 °C. It will be shortened if the mean anode current is reduced, or the mercury temperature is decreased.

The maximum mean anode current is equivalent to the direct current which may continuously flow through the tube. As the current flow in thyratrons is usually discontinuous and often takes the form of impulses, the maximum mean anode current is stated as well as the maximum peak anode current in the published data. The latter is that value of anode current which may be permitted during a short period without overheating the anode or destroying the cathode by excessive ion bombardment. Usually two values are stated; one for an anode current with a frequency above 25 cycles per second, and the other for a frequency below 25 cycles per second. Because the duration of a current impulse is greater at lower frequencies, more heat is generated and also the cathode is bombarded by a greater number of ions. The maximum permissible peak anode current is therefore smaller.

The maximum mean anode current is a decisive factor in determining the load which may be applied in the anode circuit of a thyratron. In case of discontinuous load the mean current should be calculated from the averaging time stated in the published data. Assuming that the technical data of a certain

*) This is not correct in case of the so-called gas triodes which can be used for instance for generation of saw-tooth oscillations. These tubes can be rendered non-conducting by increasing the negative grid current, so that the ion cloud is absorbed by the grid. This can be achieved by increasing the negative grid bias, or by reducing the resistance inserted in the grid circuit.

thyratron tube specifies a maximum mean current of 3 amps, a peak anode current of 20 amps and an averaging time of 10 seconds, this means that during one averaging time a tube current of 20 amperes for 1,5 seconds, or a current of 10 amperes for 3 seconds, or 3 amperes for 10 seconds is permissible. The product $I_a \cdot T_{av} = 30$ A · sec should therefore not be exceeded. Generally the following condition must be satisfied:

$$\int_{t}^{t+T_{av}} i \cdot dt \leqq I_a \cdot T_{av}, \tag{3.1}$$

with the additional condition that the anode current i never exceeds the maximum permissible peak value.

As stated before, tubes with different gas fillings behave in different ways. For example, the control characteristics of mercury-vapour filled thyratrons are dependent on temperature; with increasing temperature the characteristics are shifted toward the region of increasing negative grid voltage (fig. 3–2). The de-ionisation time is rather high (approx. 1000 μs), so these tubes can be used only in circuits working at low frequencies (up to approximately 500 c/s).

The tubes should be mounted vertically, socket downwards, in order that the liquid mercury shall flow to the bottom of the tube. The cathode should be switched on for several minutes before switching on the anode circuit in order to evaporate sufficient mercury.

The advantage of mercury-vapour filled tubes, however, is the reduced risk of arc-back, and long life. This type of thyratron is generally preferred in industrial equipment handling large powers.

If the thyratron is filled with inert gas (argon, helium, neon or xenon) the control characteristics are practically independent of temperature, as the gas pressure changes but little over the range of temperatures encountered in practice. As the life of inert gas thyratrons is considerably shortened by gas clean-up, the manufacturer endeavours to put a sufficient amount of gas into the tube. This may be done by increasing either the gas pressure or the dimensions of the bulb. For practical reasons the first method is chosen.

The maximum permissible inverse voltage decreases, however, as the gas pressure is increased, and for inert gas-filled thyratrons with normal dimensions and good life expectancy it is usually not greater than approximately 1300 V. On the other hand, mercury-vapour filled thyratrons can easily be made suitable for inverse voltages up to 30 kV. Inert gas-filled thyratrons have very short de-ionisation times (in the order of some microseconds), so they are suitable for circuits working at fairly high frequencies (up to 150 kc/s). These tubes may be operated in any position.

In addition to single-grid thyratrons (triodes) there are gas-filled tubes having two grids (tetrodes). The advantages of tetrodes are: low control-grid current, small capacitances between anode and control grid, and the possibility of altering the control characteristic by varying the screen-grid voltage.

The introduction of the additional screen grid considerably reduces the current flowing to the control grid when the tube is non-conducting. This may be as low as a few microamperes, which may be of importance in cases where a high resistance is inserted in the grid circuit. If the control grid current is large a considerable voltage drop will appear across this resistance, shifting the ignition point and thus changing the operating conditions of the tube. A tetrode will therefore be preferred in those circumstances.

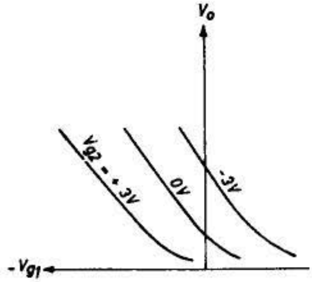


Fig. 3-3. Control characteristics of a tetrode thyratron.

Due to the small capacitance between anode and control grid, the grid circuit of a tetrode is almost independent of the anode circuit, so the risk of unintentional firing is small. For instance, in circuits where thyratrons are ignited by impulses applied to the control grid via a transformer, and the thyratron is a triode with a high grid-to-anode capacitance C_{ag}, it could happen that an impulse occurring unintentionally in the anode circuit is transferred via C_{ag} to the grid, thus firing the tube. In such a circuit a tetrode would give a better performance.

The third advantage of a tetrode is the possibility of shifting the control characteristic over a certain range. This can be done by adjusting the screen grid voltage V_{g2}, as is shown in fig. 3–3. It is of value in special circuits where it may be necessary to match two tubes having slightly different characteristics. Furthermore, small alterations of tube characteristics occurring during life can be compensated by screen-grid voltage adjustment.

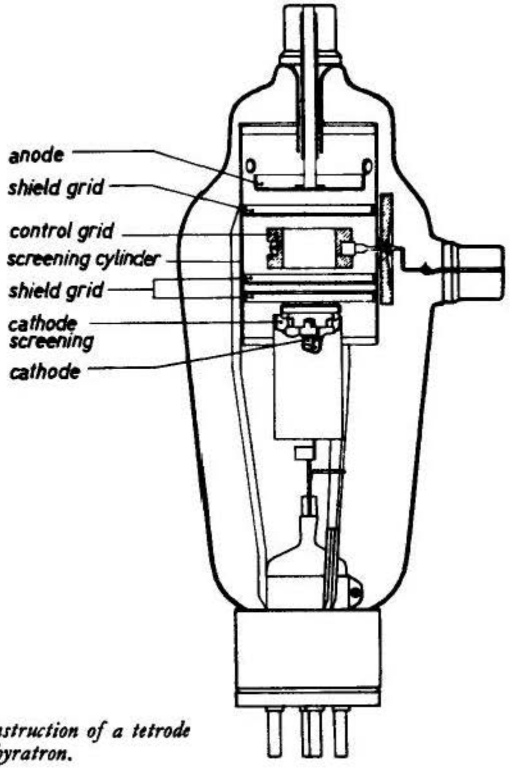


Fig. 3-4. Construction of a tetrode thyratron.

Finally, in special cases the screen grid can be used as an additional control electrode for igniting the tube.

In the published data of thyratrons the maximum permissible anode voltage is always stated. This value must not be exceeded during operation, otherwise the tube may ignite even though a high negative grid bias is applied. The inverse voltage limitations (anode negative with respect to the cathode) must be observed. If the inverse voltage exceeds the permitted value, current may flow through the tube in the reverse direction (arc-back). The occurrence of arc-back depends, among other factors, on the density of gas ionisation, and this again depends on the frequency of the anode current, so the maximum permissible inverse voltage is lower when operating at high frequency. Furthermore, because the inverse voltage is influenced by the gas pressure, the permissible inverse voltage of tubes with mercury vapour filling is to a certain extent dependent upon the temperature, being considerably reduced as the temperature rises.

Fig. 3-4 shows the internal construction of a tetrode thyratron. The bulb consists of thick glass to withstand the rough treatment which may be encountered in industrial service. The anode is made of metal or graphite and is specially shaped to provide good heat dissipation and thus to avoid excessive temperature rise and the consequent risk of secondary emission. The cathode is oxide coated, and is capable of giving high emission. Directly or indirectly heated cathodes may be used, their construction differing, however, from those used in high-

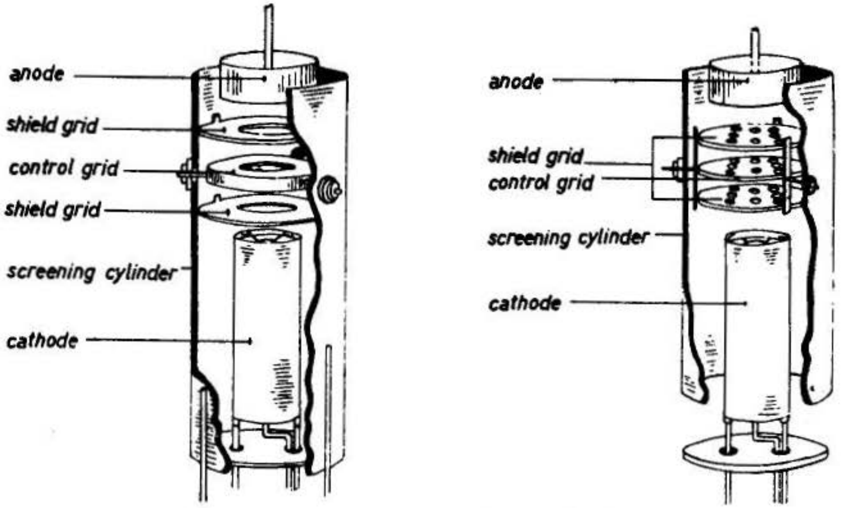


Fig. 3-5. Tube assemblies with negative (left) and positive (right) control characteristic.

vacuum tubes. As the electron paths in gas-filled tubes need not be straight lines, the cathodes may be for instance helical, thus increasing the thermal efficiency of the cathode by reducing radiation losses.

The warming-up time ranges from some seconds to several minutes according to the kind and size of the cathode. It should be noted that a longer warming-up period is required in the case of mercury-vapour filled tubes, to ensure that a sufficiently high gas pressure has been reached before load is applied to the anode circuit of the tube.

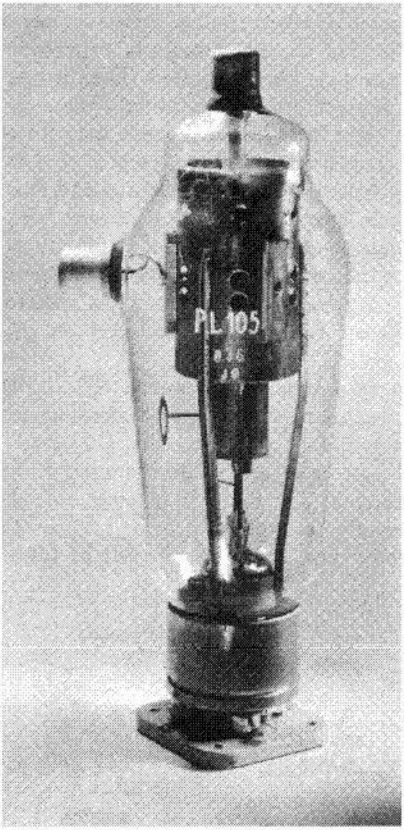


Fig. 3-6. Philips PL 105 tetrode thyratron.

The control grid generally takes the form of a ring or screen and consists of graphite or metal. Thyratrons with negative control characteristics have an annular control grid with a rather wide aperture. Tubes with positive control characteristics usually contain a system of perforated metal screens (see fig. 3–5). It is obvious that on account of the screening thus provided, firing occurs only at positive values of the control-grid voltage.

In tetrode thyratrons, the additional grid, screening the control grid from anode and cathode, also consists of perforated metal screens. The construction of tetrode assemblies is illustrated in figures 3–4 and 3–5. Fig. 3–6 shows a tetrode thyratron (Philips PL 105) designed for an average anode current of 6.4 amperes.

In most practical applications, thyratrons will be used as rectifying elements and fed with an alternating voltage. The anode voltage is therefore sinusoidal, as is shown in fig. 3–7. Obviously the instant of firing can then be determined by the value of the negative bias applied to the control grid. In the example shown, the thyratron will ignite at $V_g = 0$ V (*d*) only with a small delay (*d'*), but this delay will increase as the negative grid voltage is increased (*c*, *b*).

If for every value of the sinusoidal anode voltage the corresponding ignition value of the grid voltage is plotted as a function of time, the "igniting characteristic" of the thyratron is obtained (fig. 3–8, broken line). By means of this igniting characteristic the retarded firing of the tube as a consequence of

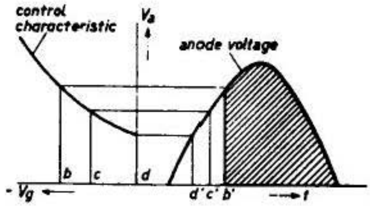


Fig. 3-7. Firing delay by negative grid bias.

varying the negative grid voltage can be well illustrated. The straight line corresponding to the grid voltage $V_{g(1)}$ intersects the igniting characteristic at the point A, so firing takes place and anode current will flow from this point to the end of the half cycle. If the grid voltage is increased to $V_{g(2)}$ the control characteristic is intersected at the point B, and it can be seen that the conducting time is then shorter. Since the hatched area is a measure for the power passed by the thyratron, it is obvious that, for instance, the output power of a rectifier equipped with such tubes can be controlled by varying the grid voltage.

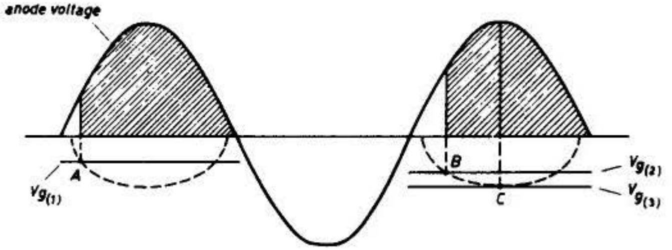


Fig. 3-8. Firing delay up to 90 degrees by negative direct grid voltages.

However, it can be seen from fig. 3–8 that control is possible only until point C is reached, i.e. up to a "firing angle" of 90 degrees, if only direct voltages are applied to the control grid. To extend the firing range up to 180 degrees, an alternating voltage is applied to the grid, the phase of this voltage with respect to that of the anode voltage depending on the desired firing angle (fig. 3–9).

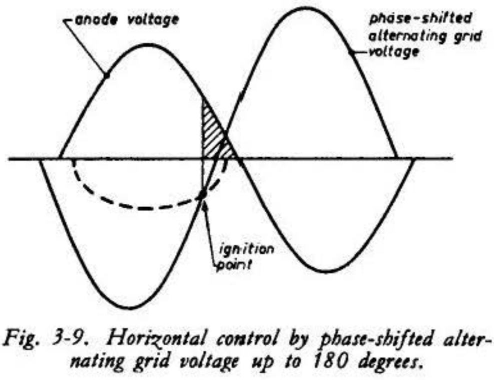


Fig. 3-9. Horizontal control by phase-shifted alternating grid voltage up to 180 degrees.

This method of controlling the ignition point is called horizontal control, because the alternating grid voltage is shifted horizontally on the time axis.

In many cases grid control by a sinusoidal voltage is not quite sufficient to obtain accurately timed firing on account of the inevitable tolerances on the igniting characteristic due, for instance, to its dependency on temperature etc. In these circumstances ignition can be initiated by impulses which are superimposed on a negative grid bias. The phase of these impulses is shifted with respect to the anode voltage by the firing angle a (fig. 3–10). The impulses are often generated by a special peaking transformer schematically shown in fig. 3–11.

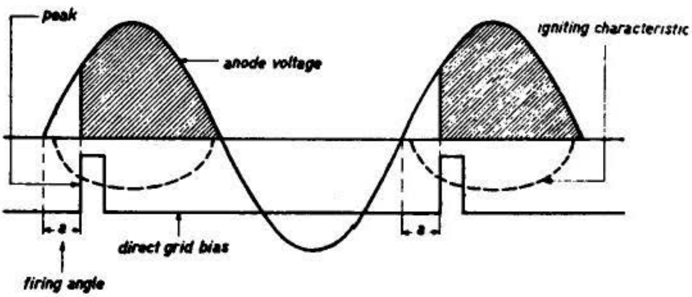


Fig. 3-10. Horizontal control by phase-shifted impulses.

This transformer has a primary winding p and one or more secondary windings s. The transformer core is of a material having low magnetic saturation and small cross section, so that it is saturated at low magnetic field strengths. Any further increase of the magnetic flux will be diverted to the by-pass and the air gap g. The magnetic flux B_s induced in the core of the secondary winding has the shape illustrated in fig. 3–11, and produces the peaked voltage V_s in the secondary winding.

Obviously the primary current lags with respect to the supply voltage by a certain angle, because of the inductance of the primary winding; similarly the secondary voltage peaks are shifted in phase by the same angle. However, it is often desired that the peaks appear at the beginning of the positive half cycles of the supply voltage. This can be ensured by inserting a resistor

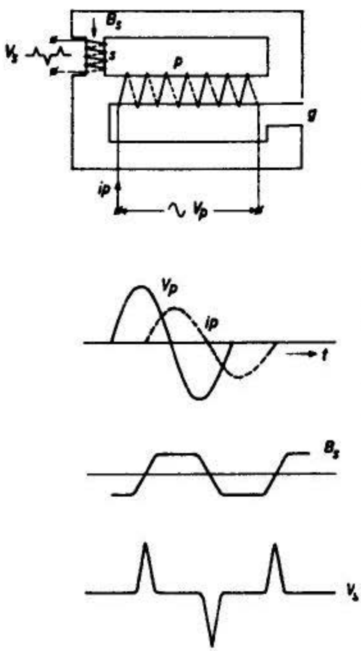


Fig. 3-11. Schematic representation of a peaking transformer.

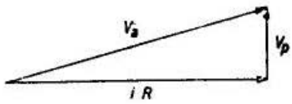


Fig. 3-12. Vector diagram showing phase conditions of peaking transformer primary when a series resistor R is inserted.

R in series with the primary winding. If this resistor is large in comparison with the reactance of the winding, the voltage V_p appearing across the winding will lead by nearly 90 degrees with respect to the supply voltage V_a, as is shown by the vector diagram of fig. 3–12. Thus the angle of lag of the peaks can be compensated.

Fig. 3–13 shows a typical peaking transformer together with a small rectifier

unit which serves as the voltage source for biasing the thyratrons.
Another method of controlling the firing angle is the so-called vertical control

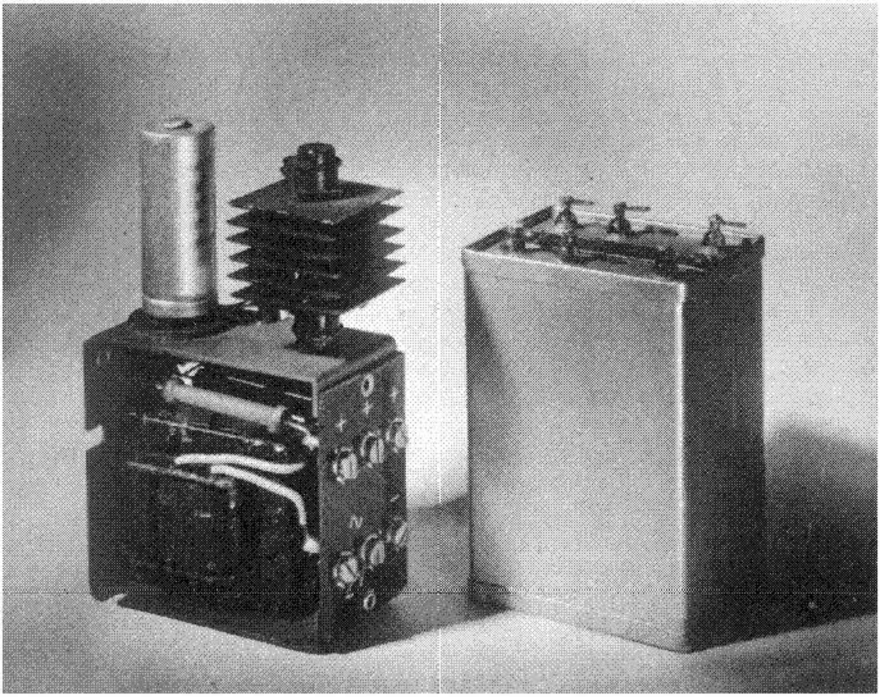


Fig. 3-13. Philips peaking transformer type 84590 (right) and rectifier unit type 1289 (left) for grid control of thyratrons.

which is often used in industrial apparatus because it requires few components (fig. 3–14). An alternating voltage lagging about 90 degrees behind the anode voltage is applied to the grid, superimposed on a direct voltage which can be varied between negative and positive values. As can be seen, the firing angle

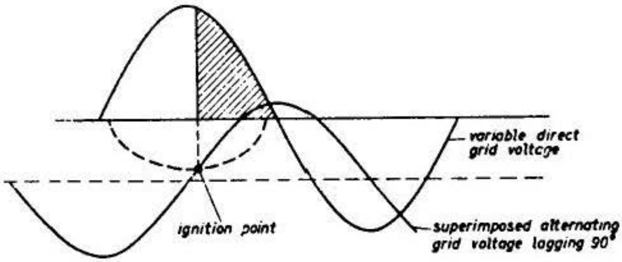


Fig. 3-14. Vertical control of thyratrons.

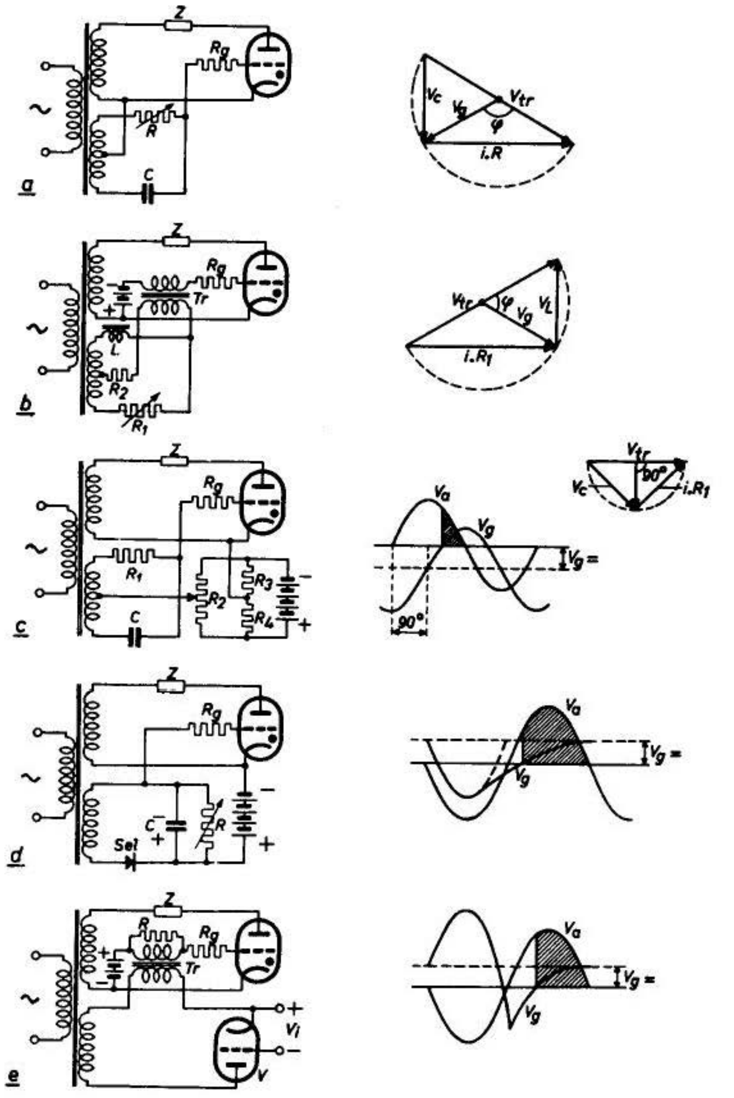


Fig. 3-15. Basic circuits for grid control of thyratrons.

can be varied between approximately 0 and 180 degrees, but it must be noted that the amplitude of the alternating grid voltage must not be too small, or it may not intersect the ignition characteristic, particularly at large firing angles.

A disadvantage of the vertical control is that the cathodes of simultaneously controlled thyratrons must have the same potential as the control is exercised by a direct voltage. This presents no difficulties in the case of multi-phase rectifiers, but if two tubes connected "back-to-back" are to be controlled, as is the case in electronic welding contactors, light-dimming equipment and the like, vertical control cannot be used. In these cases horizontal control has to be adopted or one of the special circuits described later.

A number of typical basic circuits for retarded firing of thyratrons are reproduced in fig. 3–15. Circuit (*a*) shows a simple horizontal control by a phase-shifted alternating voltage. The anode circuit of the thyratron includes an impedance Z representing the load. The grid voltage is taken from a phase-shifting network consisting of the transformer secondary winding, a capacitor C and a variable resistor R. As shown by the corresponding vector diagram, the voltage across the capacitor lags about 90 degrees behind the voltage appearing across the ohmic resistance. As the sum of both voltages must always be equal to the transformer voltage V_{tr}, the top of the vector symbolizing the output voltage V_g moves on a semi-circle whose diameter is the vector of the transformer voltage V_{tr}. The magnitude of the output voltage V_g remains constant and is equal to the half of the transformer voltage, but its phase is shifted by an angle φ which may be varied over the range of approximately 0 to 180 degrees by altering the value of R. As will be shown later, if the load is inductive (which is generally the case), a much smaller range of firing angle is needed to control the tube current from zero up to its full value. The curves of the grid and anode voltages present in a circuit according to fig. 3–15*a* have been already shown in fig. 3–9.

Circuit (*b*) shows the horizontal control by phase-shifted peaks illustrated in fig. 3–10. Here again a phase-shifting network is employed. It consists of an ohmic resistor R_1 and an inductance L. The corresponding vector diagram is shown at the side and needs no further explanation. The output voltage of the phase-shifting network is applied to the primary winding of a peaking transformer *Tr* via a resistor R_2 which serves for phase correction. The grid circuit of the thyratron consists of the secondary winding producing the peaks and a d.c. source supplying the negative grid bias.

In circuit (*c*) is shown vertical control using a variable direct grid voltage and superimposed alternating voltage which lags by about 90 degrees. The latter is generated by a network consisting of C and R_1, in which $R_1 = 1/\omega C$. The direct grid voltage, which may vary between positive and negative values, is taken from the slider of the potentiometer R_2 which forms a bridge circuit together with the equal resistors R_3 and R_4. With this circuit also a firing angle range up to 180 degrees is obtainable. For the sake of simplicity in the illustration of the voltage curves the igniting characteristic of the thyratron is assumed to coincide with the zero axis.

In circuit (*d*) a device is shown which is neither a vertical nor a horizontal control. The tube is given a positive grid bias by a d.c. source. During the negative half cycles of the alternating anode voltage the capacitor C will be charged via a selenium rectifier *Sel* with the polarity indicated. In the following (positive) half cycle the capacitor will discharge through the variable resistor R. The form of the voltage present at the tube grid is shown at the side, and as is seen the voltage curve intersects the zero axis at a definite instant as determined by the value of the discharge resistor R, whereupon the tube becomes conductive.

Circuit (*e*) illustrates a grid control which may be used successfully when several thyratrons whose cathodes have not the same potential are to be controlled, for instance, in welding control devices. The amplifying tube V is connected in such a way that it passes current during the negative half cycle of the anode voltage, so that during this period a current impulse flows through the primary winding of transformer *Tr.* As a result, a voltage is induced in the secondary winding and has the form shown at the side. It will be seen that the

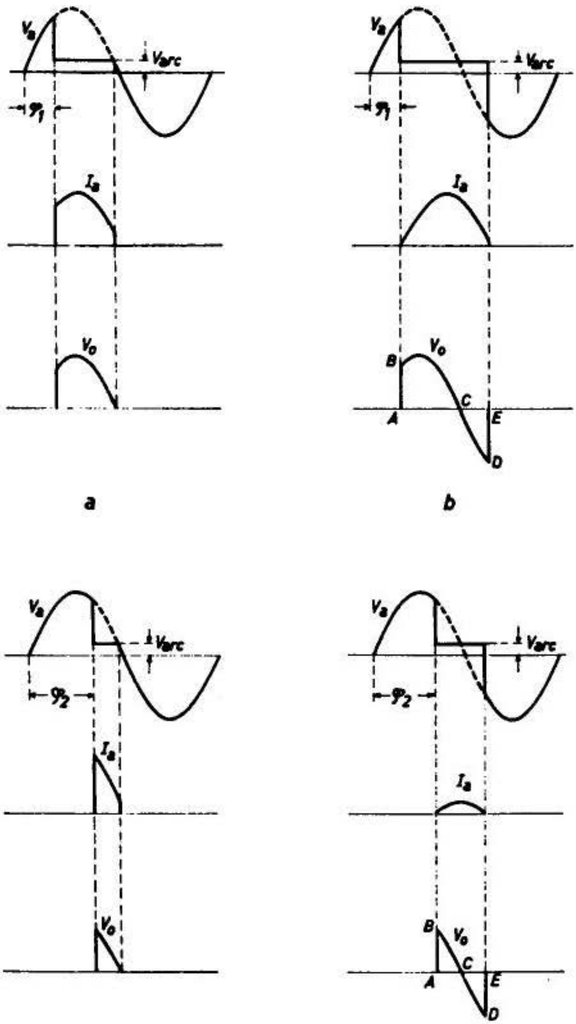


Fig. 3-16. Voltage and current curves at different firing angles (a) with resistive load, (b) with mixed resistive and inductive load.

thyratron is blocked at the beginning of the following positive half cycle of anode voltage. But the grid voltage again passes through the zero axis because of the positive bias applied to the grid circuit, and the thyratron fires. The firing angle may be varied by adjusting the negative control voltage V_i applied to the grid of the amplifying tube *V*. If the current through this tube is reduced by increasing voltage V_i, a smaller current impulse flows through the primary winding of *Tr*, and the voltage appearing across the secondary winding swings negative for a shorter time, thus passing the zero axis at an earlier moment and reducing the firing angle of the thyratron.

All circuits shown in fig. 3–15 contain a protective resistor R_g which is inserted in the grid circuit of the thyratron. It serves to limit the grid current and will usually have a value between 10 kΩ and 50 kΩ.

The methods of grid control described above are widely used in electronic equipment. There are numerous variants, of course, but they are all derived from one or other of these basic circuits.

The way in which the anode voltage and current are affected by change of firing angle must now be considered. In fig. 3–16 the voltage and current curves are depicted for several values of the firing angle φ. At (*a*) pure ohmic load is assumed whilst (*b*) shows the curves when the load is inductive. In the first case current and voltage are in phase, so the current half wave will be "cut" if the firing angle increases. Moreover it is seen that the whole firing angle range from 180 to 0 degrees is needed for current control from zero up to its full value. In case of an inductive load the current wave lags with respect to the voltage curve, so the full current wave may pass the thyratron even if the firing point is retarded by a certain angle φ_1. On the other hand the average current approaches zero for firing angles φ_2 which are smaller than 180 degrees, so it is evident that the firing angle range needed for full regulation is considerably smaller than in the case of a purely resistive load. When the load is entirely inductive the current flow ceases at the moment when the area *CDE* is equal to the area *ABC*. However, if there is a resistive component of load (which will always be so in practice) the current flow ceases earlier. The difference between *ABC* and *CDE* is then equal to the voltage drop resulting from the resistive load component.

As mentioned before, it is possible to construct rectifiers with thyratrons in which the output power may be easily adjusted by grid control in any way desired. The basic circuits used in this application are the same as described in the preceding chapter. Practically all that was previously said concerning the behaviour of gas-filled rectifying tubes is equally valid for thyratrons because as soon as they become conductive they behave just like gas-filled diodes. The various control circuits, however, will be described in detail in the second part of this book.

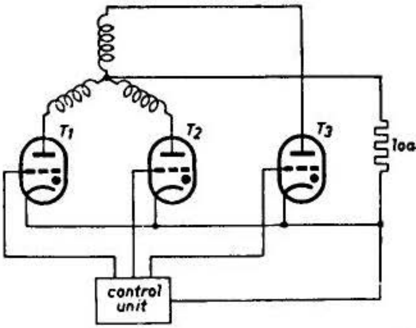


Fig. 3-17. Block diagram of a controlled three-phase rectifier.

In fig. 3–17 the block diagram of a controlled three-phase rectifier is shown. Assuming firstly that the load is purely resistive, an output voltage is obtained which, plotted as a function of the firing angle φ_0 (now measured from the intersection of two successive anode voltage waves) is of the form depicted in fig. 3–18 for three different values of φ_0. On the left of this figure the output voltage is shown for the case of unretarded firing. Each tube passes current during the time interval $\tau = 2\pi/m$, m being 3 in the case considered. In the centre of the diagram the voltage curve is shown for a firing angle $\varphi_0 = \bar{\varphi}$, where the output current is not yet interrupted, and the conducting time τ per

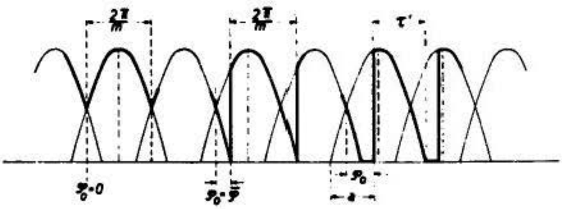


Fig. 3-18. Output voltage of a multi-phase rectifier at different firing angles (resistive load assumed).

anode is still not reduced. On the right the output voltage is plotted for a larger firing angle. As is seen, the conducting time τ' has become shorter, and the output current is no longer continuous, but is interrupted at regular intervals.

The general expression for the output voltage of an m-phase controlled rectifier with ohmic load, in terms of the firing angle φ_0, is:

$$V_o' = \frac{m}{2\pi} \cdot \int_{\frac{\pi}{2} - \frac{\pi}{m} + \varphi_0}^{\frac{\pi}{2} + \frac{\pi}{m} + \varphi_0} \sqrt{2}\, V_{tr} \cdot \sin\varphi \cdot d\varphi =$$

$$= \sqrt{2} \cdot \frac{m}{\pi} \cdot \sin\frac{\pi}{m} \cdot V_{tr} \cdot \cos\varphi_0 = M\, V_{tr} \cdot \cos\varphi_0. \quad (3.2)$$

This voltage differs from the output voltage of an uncontrolled rectifier only in respect of the factor $\cos\varphi_0$. However, the equation (3.2) is valid only when the conducting time τ is not reduced, i.e. $\varphi_0 \leqq \bar{\varphi}$, where $\bar{\varphi}$ obviously is given by

$$\bar{\varphi} = \frac{\pi}{2} - \frac{\pi}{m}. \quad (3.3)$$

If the firing angle is $\varphi_0 > \bar{\varphi}$, the reduced conducting time per anode is

$$\tau' = \frac{\pi}{2} + \frac{\pi}{m} - \varphi_0, \quad (3.4)$$

and the output voltage of an m-phase rectifier becomes:

$$V_o' = \frac{m}{2\pi} \int_{\frac{\pi}{2} - \frac{\pi}{m} + \varphi_0}^{\pi} \sqrt{2}\, V_{tr} \cdot \sin\varphi \cdot d\varphi = \sqrt{2}\frac{m}{2\pi} \cdot \left[1 - \sin\left(\varphi_0 - \frac{\pi}{m}\right)\right] \cdot V_{tr}. \quad (3.5)$$

As can easily be seen from fig. 2–15, in a two-phase rectifier the anode conducting time will always be reduced if $\varphi_0 > 0$. This conducting time is $\tau' = \pi - \varphi_0$. The output voltage of a controlled two-phase rectifier is according to equation (3.5):

$$V_o' = \frac{\sqrt{2}}{\pi} \cdot (1 + \cos\varphi_0) \cdot V_{tr}. \quad (3.6)$$

If the firing angle φ_0 is not measured from the intersection of two successive anode voltage waves, but is referred to the point at which the anode wave crosses the zero axis (see fig. 3–10), then:

$$a = \varphi_0 + \frac{\pi}{2} - \frac{\pi}{m}. \tag{3.7}$$

as can be seen from fig. 3–18.

Things are quite different, however, if the load of the rectifier is mainly inductive. In this case the current from each anode continues until the following anode becomes conductive. This is shown in fig. 3–19 for different firing angles,

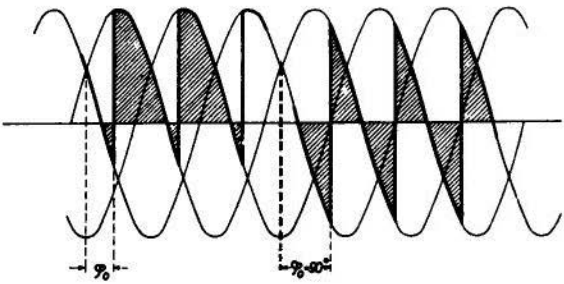


Fig. 3-19. Output voltage of a multi-phase rectifier at different firing angles (inductive load assumed).

$m = 3$ assumed. As the hatched areas below the zero axis must be subtracted from those above the zero axis, the output voltage is lower than in the case of a resistive load. For a firing angle $\varphi_0 = 90°$ the resulting output voltage is zero for inductive load, although in the case of a resistive load an output voltage will still appear, and will be equal to:

$$V_o' = \frac{3\sqrt{2}}{2\pi} \cdot \int_{120°}^{180°} \sin\varphi \cdot d\varphi \cdot V_{tr} = 0{,}34\ V_{tr}. \tag{3.8}$$

In the case of two-phase rectification and an inductive load the mean output voltage is:

$$V_o' = \frac{\sqrt{2} \cdot V_{tr}}{\pi} \int_{\varphi_c}^{\varphi_0 + \pi} \sin\varphi\, d\varphi, \tag{3.9}$$

since in this case each tube conducts during 180°. Integration gives:

$$V_o' = \frac{\sqrt{2} \cdot V_{tr}}{\pi} \cdot \left\{ \cos\varphi_0 - \cos(\varphi_0 + \pi) \right\} = \frac{2\sqrt{2}}{\pi} \cdot V_{tr} \cdot \cos\varphi_0. \tag{3.10}$$

It is thus seen again that for $\varphi_0 = 90°$ the output voltage becomes zero, whereas in the case of a resistive load, an output voltage of

$$V_o' = \frac{\sqrt{2} \cdot V_{tr}}{\pi} = \frac{V_o}{2}. \qquad (3.11)$$

will still be present according to equ. (3.6).

Parallel connection of thyratrons in order to obtain higher powers is usually not practicable unless special precautions are taken. The reason is that one tube will always fire first and, as the arc voltage is lower than the ignition voltage of the other tubes, the first tube to fire will take over the whole load. To avoid this, resistors R_a can be inserted into the anode leads (fig. 3–20). When the first

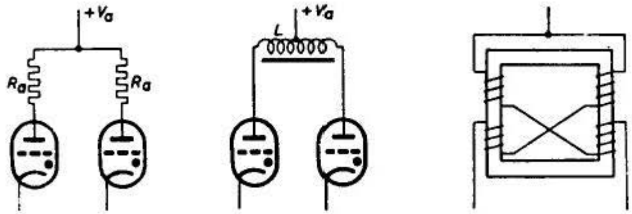


Fig. 3-20. Parallel connection of two thyratrons.

tube fires, a voltage drop appears across the resistor in its anode circuit; this voltage may be large enough to equal the difference between ignition voltage and arc voltage, thus permitting the second tube to fire also. A still better arrangement is the use of a balance choke. When the first tube fires, a voltage is induced in the other half of the winding by the sudden current rise, and this ensures immediate ignition of the second tube. Moreover, the power lost in the balance choke is much smaller than that in anode resistors. Fig. 3–20 shows schematically the construction of such a choke; the two halves of the winding are cross-connected for better performance; the iron core has no air gap.

The burning life of thyratron tubes is approximately the same as that of gas-filled rectifying tubes, as far as the effects of ion bombardment of the cathode and gradual reduction of gas pressure are concerned. The cathode is either of the shielded type or a special cathode is used in which the emitting oxide coating is located on the inner surfaces of a multiple subdivided hollow cylinder.

There is, however, a further risk which must be guarded against. If a portion of the emissive cathode coating should evaporate and be precipitated on the grid, the grid will emit electrons (grid emission). It will then lose its ability to control the tube. By special treatment of the grid surface and other constructional features, however, the danger of grid emission can be practically eliminated. Moreover this effect is less likely to occur in tetrodes, because in these tubes the control grid is well shielded from the cathode by the screen grid (see fig. 3–4).

As already mentioned, the control of thyratrons often is affected by phase-shifting networks containing both resistance and inductance or a capacitance. In fig. 3–21 is given an abac for determining the phase angle φ of such networks. A more exact calculation, however, can be made by applying the formula

$$\varphi = 2 \tan^{-1} (\omega RC) \qquad (3.12)$$

for RC networks, and

$$\varphi = 2 \tan^{-1} \left(\frac{\omega L}{R} \right) \tag{3.13}$$

for *RL* networks.

Attention is drawn to the fact that in all circuits equipped with thyratrons provision must be made to ensure that the tubes are given sufficient time to heat up. The anode voltage may therefore not be applied before the filament current has been switched on for a certain time as specified in the data published bij the tube manufacturer.

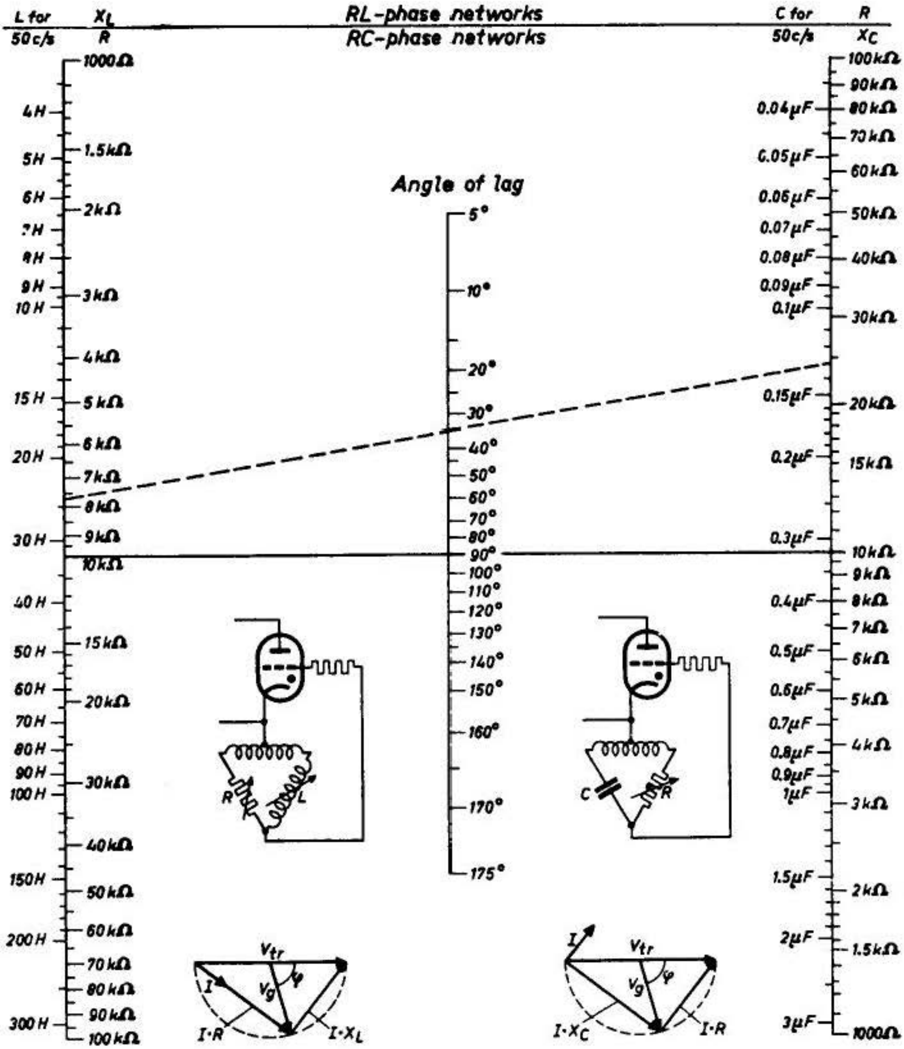


Fig. 3-21. Tab'e and abac for determining the phase angle of RL and RC networks.

4. SENDITRONS

Another type of tube often employed in industrial applications as a quick-acting electronic switch or relay is the senditron. It is able to carry instantaneously very heavy currents — up to several thousand amperes. Compared with mechanical contactors, contactor devices equipped with senditrons are much more reliable, more precise in operation, and often less costly. Unlike that of the thyratron, the cathode of the senditron consists of liquid mercury, as in the familiar mercury-pool rectifier valve. There is, however, an important difference between the method of starting the senditron and of starting the mercury-pool rectifier.

In starting the latter, the connection between the mercury pool and an igniting electrode has to be interrupted — usually by mechanical means, for instance by tilting the tube — when the arc so produced initiates the main discharge between cathode and anode. During operation a small hot spot is produced on the cathode, and moves at high speed over the surface of the mercury. Since this cathode spot disappears, and the discharge ceases immediately the discharge current falls below a certain value, one or more auxiliary anodes are usually provided in order to maintain the cathode current should the main discharge current become too small. Repetition of the rather complicated starting process, which would otherwise be necessary, is thus avoided. However, this device has the disadvantage that it involves additional current consumption by the auxiliary anodes. There is also the risk of arc-back as the result of permanent ionisation.

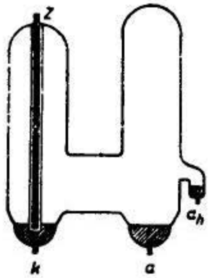


Fig. 4-1. Diagrammatic view of a senditron.

In the senditron, however, it is not necessary to maintain the cathode hot spot. The firing procedure is simplified in such a way that the tube can be fired practically instantaneously at an accurately determined time, and the firing cycle may be repeated at very small intervals of time up to a specified upper limit of frequency.

The senditron contains a capacitive igniter, the operation of which can be explained by reference to fig. 4–1. An igniting electrode Z extends downwards into the mercury pool k, but is insulated from the mercury by a thin layer of dielectric material. If a sufficiently high voltage is applied between the igniting electrode and the cathode, the electric field strength will be sufficient to produce a small amount of electron emission ("field emission") *).

A high voltage momentarily applied to an auxiliary electrode a_h accelerates these electrons, which attain sufficiently high speeds to ionize the mercury vapour atoms by collision, thus starting the main discharge. As in all gas-filled discharge tubes, the discharge will be interrupted when the anode voltage drops below the value of the arc voltage.

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*) Until recently it was thought that the field strength between the igniting electrode and the mercury cathode was not sufficient to produce field emission. Later investigation, however, suggests that the field causes the mercury surface to deform; small peaks of mercury arise and cause local concentration of the field up to the intensities necessary for field emission. The theoretically calculated time needed for deformation agrees well with the small time delays, in the order of 10^{-6} seconds, observed by actual measurement.

Not only the cathode *k*, but also the anode *a* and auxiliary electrode a_h consist of liquid mercury. If other materials were used, the anode material would slowly erode during the life of the tube, and might contaminate the mercury surface of the cathode, causing irregular firing.

The advantage of senditrons over thyratrons with heated cathodes is that the mercury pool cathode is able to deliver currents up to many thousands of amperes. In some applications a high but only momentary current impulse is desired, the duration of which is small compared with the subsequent pause, so that the mean current, averaged over the complete cycle, is much smaller than the peak value. Since it is the product of the mean current and the arc voltage which constitutes the effective power dissipated in the tube, senditrons of small dimensions can switch very large current pulses of short duration.

A senditron, Philips type PL 5, of a type normally used in electronic equipment is illustrated in fig. 4–2.

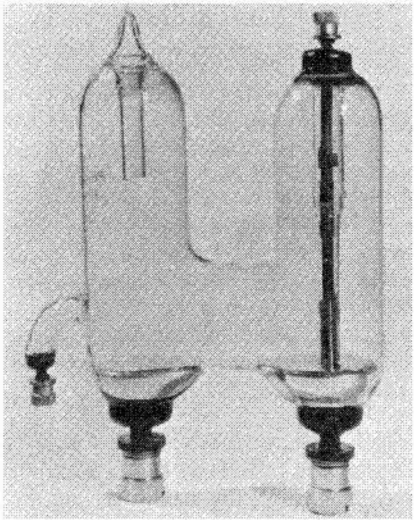


Fig. 4-2. Philips PL 5 senditron.

The great advantage of the capacitive ignitor used in senditrons is the very small energy required for starting the main discharge (approximately 6 milliwatt-seconds). Senditrons are therefore particularly suitable for controlling small welding machines when the ignitron tubes, described in the next chapter, would be too expensive.

One of the most important applications of the senditron is in resistance welding, and particularly in spot-welding control systems. To ensure optimum quality of the weld, accurate control of welding time is necessary. This may be effected by the arrangement shown in fig. 4–3. Two senditrons S_1 and S_2, connected in inverse-parallel (back-to-back) are included in the primary circuit of the welding transformer, and function as an inertialess contactor. One tube carries the current during the positive half-cycles and the other during the negative half-cycles (see fig. 4–4). Firing is controlled by a special timer, the operation of which is explained in Chapter 12.

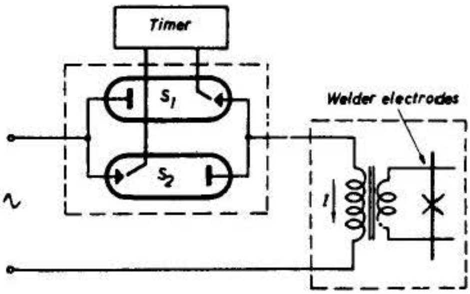


Fig. 4-3. Basic circuit of an electronic welding contactor using two inverse-parallel connected senditrons.

A welding control device using two senditrons is particularly suitable for spot welding of thin material in mass production, for instance in the toy industry and in the manufacture of precision apparatus, measuring instruments, watches, musical instruments and so forth.

A further application is the control of electronic flash-lamps for observing or recording the motion of high-speed rotating or moving objects such as propellers, motors wheels etc. The basic circuit of such a stroboscope is shown in fig. 4–5. Its action is as follows.

Assuming the flash-tube *L* to be extinguished, the capacitor *C* is charged

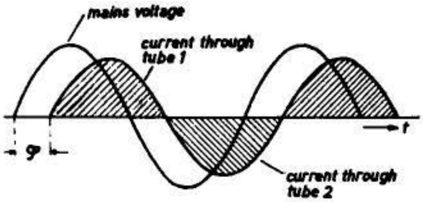


Fig. 4-4. Waveforms of currents flowing through two inverse-parallel connected senditrons.

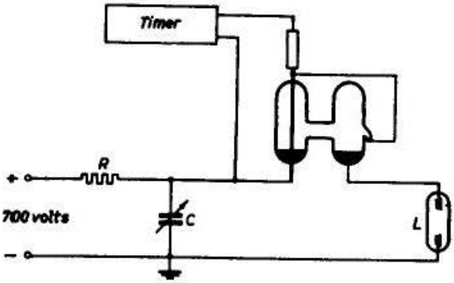


Fig. 4-5. Basic circuit of a stroboscope.

by the d.c. source via resistor *R*. To initiate the flash the senditron is made conductive, allowing the capacitor to discharge, so that a heavy current surge passes through the senditron and the flash-lamp *L*. By adjusting the value of the capacitor, the duration of the flash may be varied between 5 and 10 microseconds. The minimum interval between consecutive impulses will depend upon the time constant of the *RC* circuit, i.e. upon the values of *R* and *C*, the lower limit corresponding to the highest permissible switching frequency of the senditron, which in turn will depend upon the de-ionisation time of the gas filling.

The timer, once set, automatically controls the flash frequency by continuously switching the senditron. It will usually be synchronised at a standard frequency. The basic circuit of a timer suitable for stroboscope control is shown in fig. 4–6. It is a relaxation oscillator, the operating principle being as follows.

When the H.T. supply is switched on, the capacitor *C* charges up to the full potential of 400 volts. During the charging period the charging current causes a voltage drop across *R*, so that the grid of the thyratron EC 50 becomes negative with respect to the cathode. When *C* is almost fully charged the charging current becomes practically zero and the negative bias almost disappears, permitting the thyratron to fire. The thyratron in its conductive condition virtually short-circuits the capacitor *C* which discharges very rapidly through the tube and the primary of the ignition coil, thus inducing a very steep-fronted voltage pulse at the transformer secondary.

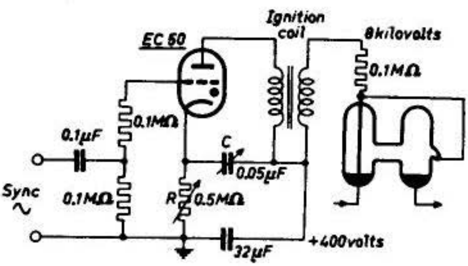


Fig. 4-6. Timer circuit suitable for the stroboscope shown in fig. 4-7.

In order to obtain the required 8 to 10 kV for firing the senditron the transformer should have a primary winding of 230 turns and a secondary of 18 000 turns.

When capacitor C is fully discharged the thyratron is extinguished and the cycle repeats. The speed of operation of the circuit depends upon the settings of R and C, and with the values specified in fig. 4–6 it is possible to vary the frequency of the impulses transferred to the ignition circuit of the senditron over the range 0.5 to 250 cycles per second.

The great advantage of the capacitive igniter with which senditrons are equipped consists in the extremely small energy (approx. 6 mW · sec) required for initiating the main discharge. In this respect these tubes compare favourably with the ignitrons, discussed in the following Chapter. Senditrons are therefore particularly suitable for small apparatus and equipment, in which the use of ignitrons would be economically impracticable.

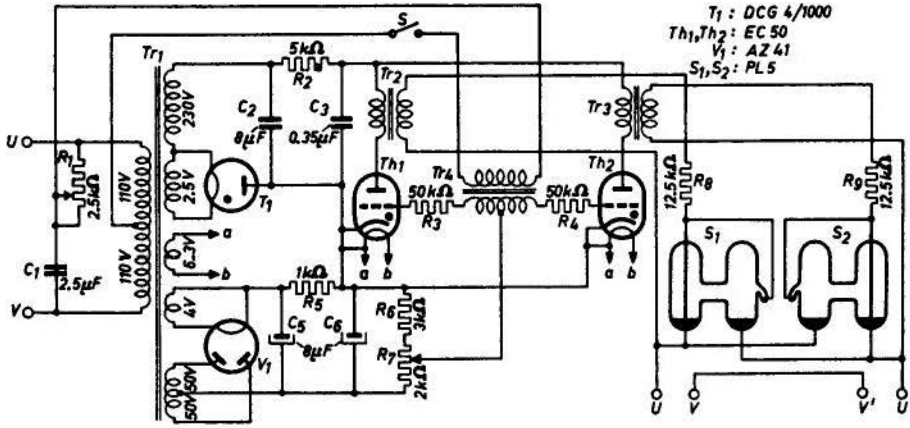


Fig. 4-7. Complete firing circuit for two inverse-parallel connected senditrons suitable for small welding equipment.

The complete firing circuit for two inverse-parallel connected senditrons, designed for a small spot-welding equipment, is shown in fig. 4–7. Its operation will be explained assuming switch S to be closed. A single-phase rectifier employing the gas filled tube T_1 charges capacitor C_3 via resistor R_2, thyratrons Th_1 and Th_2 being prevented from firing by a negative grid bias derived from the two-phase rectifier incorporating the high-vacuum tube V_1. The firing of Th_1 and Th_2 is controlled by the peaking transformer Tr_4, the secondary of which is included in the grid circuit of the thyratrons. The firing angle is controlled by the phase-shift method, the phase-shift circuit being formed by the primary of transformer Tr_1, the capacitor C_1 and the variable resistor R_1. The operation of such a phase-shifting network has been explained in the preceding Chapter.

Because the secondary of Tr_4 produces a positive and a negative peak during each cycle, which differ in phase by 180° (see fig. 3–11), the grid of Th_1 attains a positive peak potential during the first half cycle and the grid of Th_2 during the second half cycle, thus causing alternate firing of the tubes. When Th_1 is ignited, capacitor C_3 discharges rapidly through Th_1 and the primary of transformer Tr_2, and the steep-fronted current surge through this winding produces a high voltage peak of about 8 to 10 kV at the secondary, thus igniting senditron S_1.

Due to the inductance of the primary winding of Tr_2, the discharge current will be maintained long enough for C_3 to charge momentarilly with reverse polarity, so that for a short time a negative voltage is applied to the anode of Th_1, causing extincton of the tube.

In a corresponding manner, thyratron Th_2 and senditron S_2 are fired in the following half-cycle, and the process will repeat as long as switch S is closed. On opening the switch the generation of impulses ceases and S_1, S_2 cease to fire. By varying R_1 the phase angle, and hence the mean anode current flowing through S_1, S_2 and the primary winding of the welding transformer can be adjusted (see fig. 4-8).

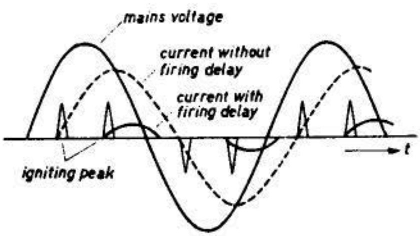


Fig. 4-8. Voltage and current curves with and without retarded firing.

The value of the alternating current flowing through two inverse-parallel connected senditrons can be derived from the average current per tube stated in the published data. Obviously the mean anode current, I_a, is equal to the integral over one half cycle of the alternating current divided by its base π, thus:

$$I_a = \frac{1}{\pi} \cdot \int_0^{\pi} I_p \cdot \sin\varphi \cdot d\varphi = \frac{2}{\pi} \cdot I_p, \tag{4.1}$$

where I_p is the crest value of the alternating current. Since each tube carries current only during alternate half-cycles, twice the value of the mean anode current may be assumed, and the r.m.s. value of the resulting alternating current flowing through the inverse-parallel connection is:

$$I_{rms} = \frac{\pi}{\sqrt{2}} \cdot I_a. \tag{4.2}$$

For example, the alternating current through two type PL 5 senditrons, which may carry an average current of 70 amperes each during 0.05 sec, will be $70\pi/\sqrt{2} = 154\ A_{rms}$ during this time.

5. IGNITRONS AND EXCITRONS

Ignitrons, which are often used in industrial equipment for controlling or rectifying very large alternating currents, are discharge tubes consisting essentially of a mercury pool cathode, an anode, and an ignition electrode which extends down into the mercury. A sectional drawing of an ignitron is reproduced in fig. 5–1. The envelope is of stainless steel and has double walls to permit the circulation of cooling water. The anode and cathode leads are of large cross-section since they have to carry very heavy currents. The mercury pool cathode is at the same potential as the steel jacket, and the anode lead is insulated by a glass-metal seal.

The ignition electrode or ignitor, which is a rod of refractory material (boron carbide), and is shaped like the pointed end of a lead pencil, dips into the mercury pool but is not wetted by the mercury (see fig. 5–2). If a positive potential of about 150 volts is applied to the ignition electrode, a momentary current of approximately 10 to 40 amperes will flow, and will cause a tiny arc at the junction between the ignitor and the mercury. This arc immediately initiates the main discharge between the mercury cathode and the positive anode, the familiar small cathode hot spot appearing on the surface of the mercury. Ignition takes place by virtue of the very strong electric field which arises at the junction of the ignitor rod and the mercury pool, thus drawing electrons from the mercury.

The main discharge ceases and the cathode spot disappears if the anode voltage falls below the "arc voltage" value or if the anode current falls below a certain critical value. The arc voltage value is in the order of 12 to 18 volts as in the case of mercury vapour thyratrons, so the tube losses are small compared with the output power, and the overall efficiency, even at low output voltages, is high. Two general types of ignitron tubes are available — those designed for high peak anode currents at comparatively low voltages in the order of 250 to 600 volts, and those designed to deliver high average currents at high anode voltages up to 2400 volts. The former are mainly intended for the control of welding equipment and the latter for the rectification of heavy currents.

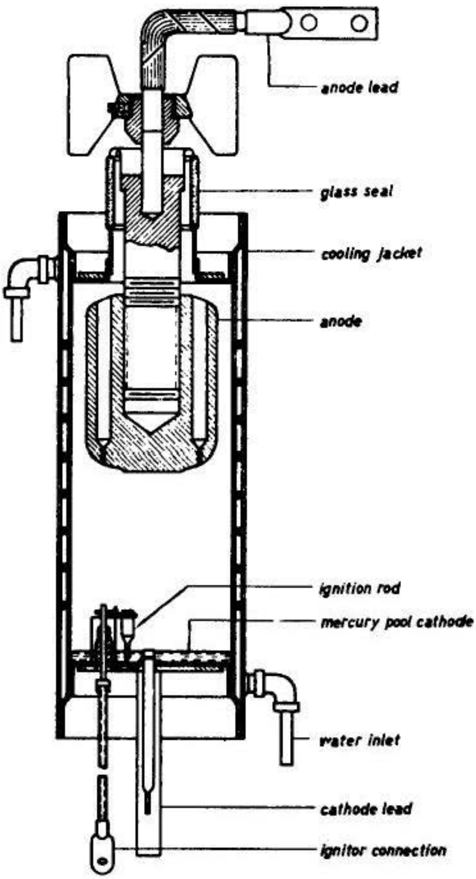


Fig. 5-1. Sectional diagram of an ignitron tube.

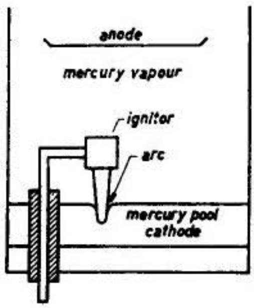


Fig. 5-2. Detail of the firing arrangement in an ignitron tube.

Rectifier ignitrons differ from welding control ignitrons in that they have additional built-in baffles between cathode and anode in order to withstand high inverse voltages up to several thousand volts. They also have a second ignitor electrode, which may be held in reserve, and an auxiliary anode is also fitted in order to maintain the cathode spot should the main anode current fall temporarily below a value of about 10 amperes, as may happen, for example, in rectifier circuits if the connected load produces a counter electromotive force.

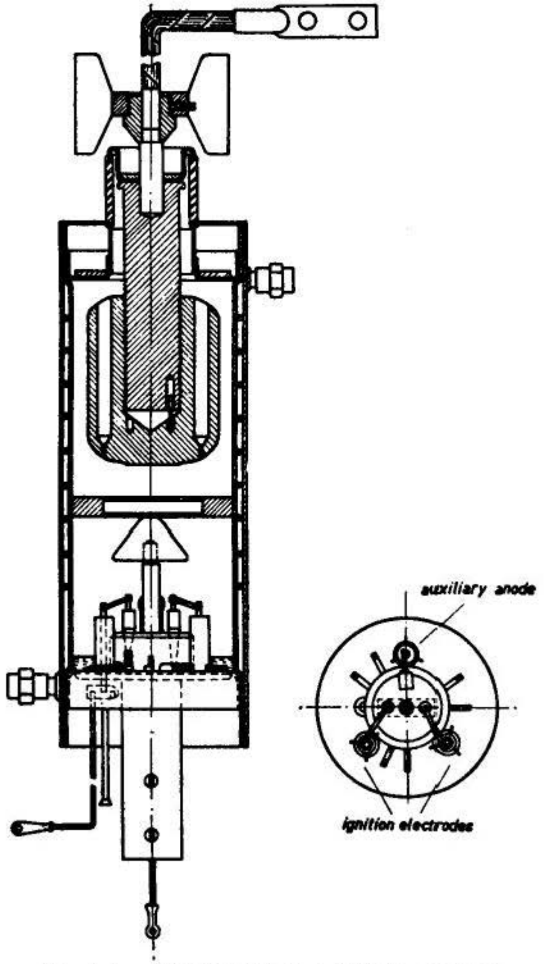


Fig. 5-3. Construction of a rectifier ignitron.

Fig. 5–3 is a sectional drawing of a rectifier ignitron. Rectifier ignitrons can, of course, be used also in welding equipment if connected in inverse-parallel. Similarly, a welding control ignitron may be used for rectification if due precautions are taken.

The limiting operating conditions for ignitron tubes are determined by the maximum permissible values of the anode voltage and of the instantaneous anode current. Another important factor is the temperature and the rate of flow of cooling water, for these not only determine the amount of power which can be dissipated but also the mercury vapour pressure within the tube. For example, the Philips Ignitron Type PL 5555 may carry an average anode current of 200 amperes. Since the arc voltage is about 17 volts, power losses of approximately 3.5 kW have to be dissipated, and because the heat capacity of the electrodes of ignitrons — as of all electron tubes — is comparatively small, temperature equilibrium is reached very quickly. Moreover, high momentary current peaks cause a rapid rise of vapour pressure in the tube, approximately 0.75 grammes of liquid mercury being vaporised for an electrical quantity of 100 ampere · seconds. Care must therefore be taken that adequate water cooling is provided to keep the gas pressure low enough to avoid arc-back or loss of control. Roughly speaking, the mercury vapour pressure is doubled for every 10 °C of temperature rise, so that the maximum permissible pressure is reached very rapidly.

The lower temperature limit is determined by the freezing point of the cooling water and by such a low vapour pressure that adequate generation of ions cannot occur. The ignitor, however, will operate successfully even in a pool of frozen mercury.

The published data of an ignitron include the values of current and voltage required for ignition and the maximum permissible positive and negative potentials at the ignitor. The positive voltage is usually equal to the anode voltage; the negative voltage must not be more than a few volts, since an inverse current would cause a cathode spot to form on the rod which would become damaged after a very short time. For this reason, a rectifying element, which passes current in one direction only, is always inserted in series with the ignitor.

An important field of application for ignitrons is the control of resistance welding equipment. The electrical portion of this equipment consists of a transformer, and means for closing and interrupting the primary circuit in order to control the duration of the welding time. The devices previously used were chiefly switches and mechanical contactors, but in many cases these have proved unable to withstand the heavy duty demanded. For example, even the currents flowing in the primary circuit are fairly large, and trouble quickly arises due to burned contacts. Again, mechanical contactors possess considerable inertia, and this affects the accuracy of timing, and thus the quality of the weld. Ignitrons, however, do not suffer from either of these defects.

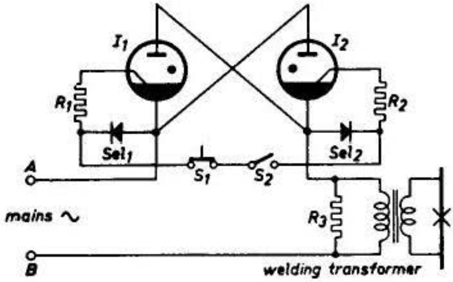


Fig. 5-4. Basic circuit of an ignitron welding contactor. Resistors R_1, R_2 are often replaced by selenium rectifiers in order to keep the inverse current through the ignitors low.

The basic circuit for welding control is shown in fig. 5–4. Here, I_1 and I_2 are the two ignitrons, which are connected back-to-back in the primary circuit of the welding transformer; R_1 and R_2 are resistors, Sel_1 and Sel_2 are selenium rectifiers, and S_1 is an automatic safety switch which interrupts the circuit if the flow of cooling water is insufficient.

Resistor R_3 across the primary of the welding transformer has two functions. The discharge in an ignitron may be considered as a number of small discharges in parallel, each carrying a current of about 10 amperes. When the current decreases, towards the end of a half-cycle, the individual discharges are extinguished in succession, until finally the last one breaks down, the current thus suddenly interrupted amounting to approximately 10 amperes. A voltage surge thus arises at the transformer primary, and might cause damage but for the fact that the primary is by-passed by R_3. Furthermore, R_3, by providing additional load, assists in maintaining the discharge if the current in the primary winding drops below the critical value.

The operation of the circuit reproduced in fig. 5–4 may best be followed by assuming that terminal B of the mains is positive at the instant switch S_2 is closed. Current then flows from B through the load to the cathode of ignitron I_2, and then via the selenium rectifier Sel_2, through S_2, S_1 and resistor R_1 to the ignitor of I_1. The current impulse now flowing through the ignitor is sufficiently great to produce a cathode spot, thus initiating the main discharge, the anode of I_1 being positive.

When the current flow through I_1 ceases, a positive potential appears at the anode of I_2 due to the inductance of the transformer winding, so that I_2 is ready to ignite as soon as the direction of the current reverses. In this way tubes I_1 and I_2 conduct alternately until the circuit is interrupted by S_2. Instead of S_2 a special mechanical or electronic timer may be employed to provide exact control of the welding time. Suitable timers will be fully described in a later chapter.

The selection of suitable ignitrons for a given welding equipment is determined by the maximum kVA demand. The output power of each type of ignitron can be ascertained from the diagrams published by the tube manufacturers. In these diagrams the kVA output obtainable from two tubes connected back-to-back is plotted as a function of the maximum average current per tube (see fig. 5-5). These diagrams are usually valid for mains supply voltages between 250 and 600 V_{rms}. For lower supply voltages the values at 250 volts apply. The diagram for the PL 5555 is valid for 2400 V_{rms} only.

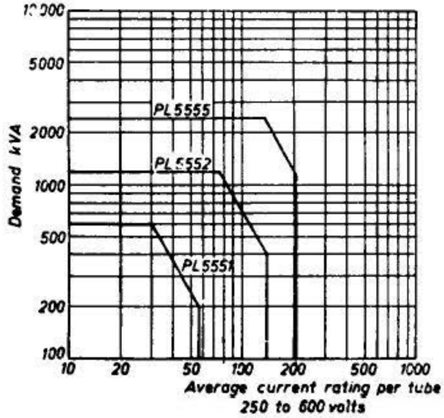


Fig. 5-5. Demand kVA ratings of ignitrons for welding equipment.

If the supply voltage is V and the kVA demand P, the r.m.s. value of the current through a pair of inverse-parallel connected tubes is:

$$I_d = \frac{1000\,P}{V}, \tag{5.1}$$

and the average value of the current per tube is:

$$I_m = \frac{\sqrt{2}}{\pi} \cdot I_d = \frac{1000\,\sqrt{2}\,P}{\pi\,V}. \tag{5.2}$$

The corresponding averaging time, T_{av}, can be calculated from the average current per tube $I_{max.}$ corresponding to the maximum kVA demand at the given supply voltage, which is assumed to flow during 0.5 seconds, and the corresponding maximum average anode current per tube, I_a, which can be taken from the diagram. Thus:

$$T_{av}\ \ I_a = \tfrac{1}{2}\,I_{max} = \frac{\sqrt{2}}{2\pi} \cdot I_{d\,max}, \tag{5.3}$$

and

$$T_{av} = 0.225 \cdot \frac{I_{dmax}}{I_a}. \tag{5.4}$$

The time, t, in each averaging time, during which a current of the average value per tube, I_m, may flow is therefore:

$$t = \frac{I_a T_{av}}{I_m}. \tag{5.5}$$

The ratio of t to T_{av} is the "duty factor", D. In the form of a percentage,

$$D = \frac{t}{T_{av}} \cdot 100 = \frac{I_a}{I_m} \cdot 100\%. \tag{5.6}$$

As an example, the kVA demand of a welding machine may be $P = 1200$ kVA at a supply voltage of 500 V_{rms}. Two ignitrons, Philips Type PL 5552 are used, and are capable of controlling a maximum load of 1200 kVA. From equation (5.1) the r.m.s. value of the demand current is:

$$I_d = \frac{1\,200\,000}{500} = 2400 \text{ amperes.}$$

From fig. 5–5 it is seen that the maximum kVA demand corresponds to a maximum average anode current per tube of 75.6 amperes. So the averaging time will be:

$$T_{av} = 0.225 \cdot \frac{2400}{75.6} = 7.1 \text{ seconds.}$$

The average value of the demand current per tube is:

$$I_m = \frac{1.41 \times 2400}{3.14} = 1080 \text{ amperes,}$$

the maximum conducting time per averaging period is:

$$t = \frac{75.6 \times 7.1}{1080} = 0.5 \text{ second,}$$

and the corresponding duty factor is:

$$D = \frac{0.5 \times 100}{7.1} = 7\% \cdot$$

This means that two PL 5552 tubes may carry an alternating current of 2400 amperes at a supply voltage of 500 volts with a duty factor of 7%. The same information can be obtained from the corresponding characteristic shown in fig. 5–6 in which the current through two inverse-parallel connected tubes is

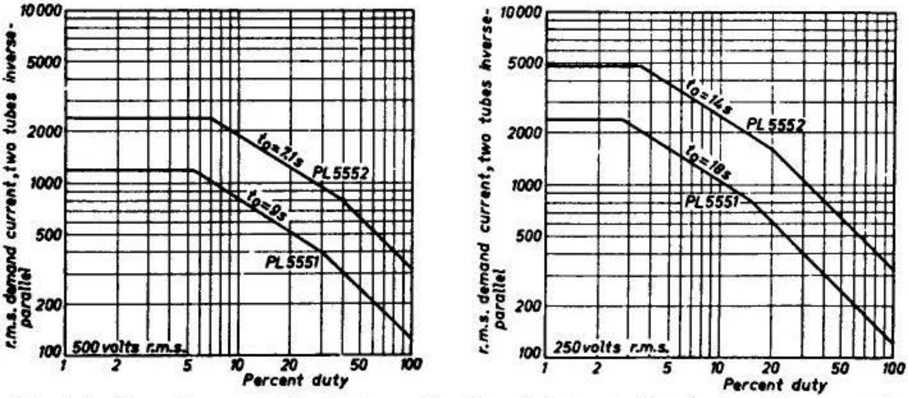


Fig. 5-6. Demand current ratings in A_{rms} as functions of the percent duty for two tubes connected in inverse parallel, for different types of ignitron and supply voltages.

plotted as a function of the duty factor, for different supply voltages and types of tube.

In some cases it may be desirable to control the power, and consequently the amount of heat applied to the work, by delaying the instant at which the ignitrons fire in each half cycle. Adjustable delay can be applied by controlling each ignitron by a separate thyratron as shown in fig. 5–7. The thyratrons T_1 and T_2 are connected in series with the ignition electrodes of I_1 and I_2 respectively. Assuming terminal B to be positive, T_1 will be fired by a positive peak applied

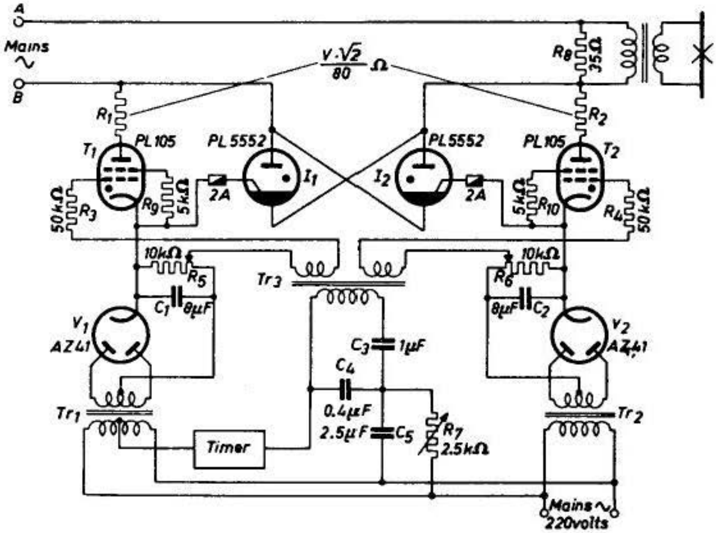


Fig. 5-7. Ignitron welding contactor with heat control.

to its control grid, and a current surge of approximately 40 amperes will flow through T_1 and the ignition electrode of I_1, firing the ignitron. In the same way I_2 will be fired via T_2 in the following (negative) half cycle. The igniting peaks applied to the grids of T_1 and T_2 are taken from the peaking transformer Tr_3, and are in antiphase. The primary of Tr_3 is fed from a phase-shifting network, the chief components of which are the primary of Tr_1, the capacitor C_5 and the variable resistor R_7. The operation of this type of phase-shifting network has already been explained in Chapter 3. The thyratrons are also given an adjustable negative grid bias supplied by two rectifiers comprising the tubes V_1 and V_2 and their associated circuits. By means of R_7 the phase delay of the peaks applied to the thyratron grids can be adjusted in order to control the mean current flowing through the ignitrons and the primary of the welding transformer, in a similar way to that previously shown in fig. 4–8.

Fig. 5–8 again shows the voltage and current curves appearing in such a circuit, with and without phase delay. For the sake of simplicity the theoretical case in which $\cos\varphi = 0$ has been assumed.

Another important application of ignitrons is in industrial rectifiers, where continuous control of the output power can be obtained by phase-delayed ignition. Such rectifiers are employed, for example, for power supply to rolling mills, conveyor belt installations, electric locomotives and so forth. The basic circuits for these applications are similar to those already described in Chapters 2 and 3. The special firing circuits, however, will be described in a later chapter. An ignitron, Philips Type PL 5555, designed for rectifying currents up to 200 amperes, is illustrated in fig. 5-9.

The life of ignitrons may be expected to be even greater than that of normal gas-filled tubes. When ultimate failure occurs it may be due to air leakage or to ignitor failure. Air leakage may be recognised by the tube passing current under certain circumstances without the ignitor being operated.

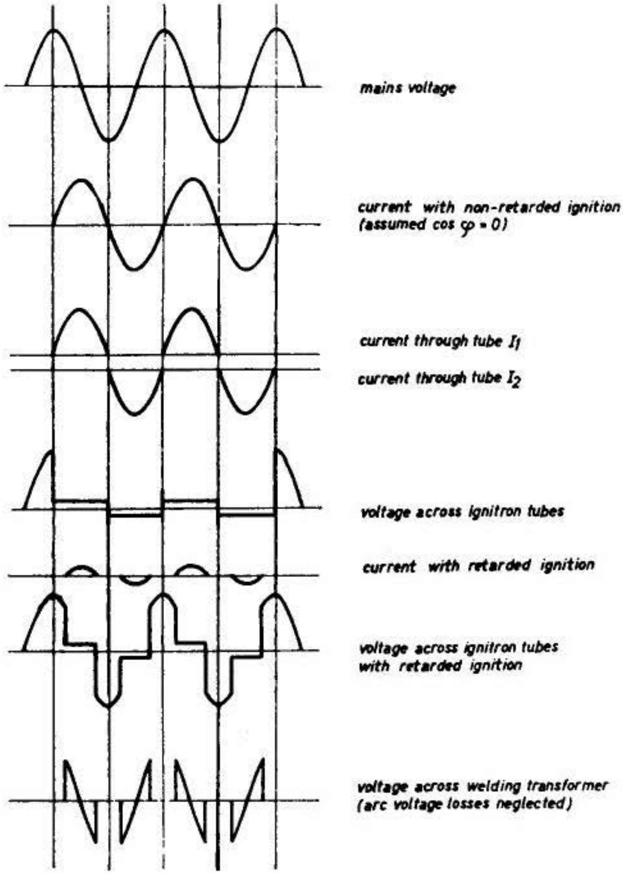


Fig. 5-8. Voltage and current curves of a device according to fig. 5-7 with and without phase delay (*cos* $\varphi = 0$ *assumed*).

The vacuum may be tested by applying a potential of from 5 to 10 kV between cathode and anode, a series resistor being included to limit the current to from 5 to 10 milliamperes. If the tube passes current for longer than one minute, gas "clean-up" may be attempted by operating the tube carefully under reduced load. If the tube again passes current when the high tension test is repeated, the tube should be replaced. Another simple test for air leakage can be made with a low frequency spark coil, connected to the anode lead. If a continuous reddish glow is seen in the interior of the tube, it has become "gassy" and should be replaced. Air leakage often causes arc-back, which is usually accompanied by severe flashing or showers of red-hot sparks visible through the anode seal.

Ignitrons with burned igniting electrodes, caused for example by reverse current, are inclined to misfire. This failure can be confirmed by measuring the resistance between the ignitor and the mercury cathode, for instance with a "Philoscope". The cold resistance in a good tube is usually between 10 and 150 ohms, but may be as low as 5 ohms or as high as 500 ohms. It may also

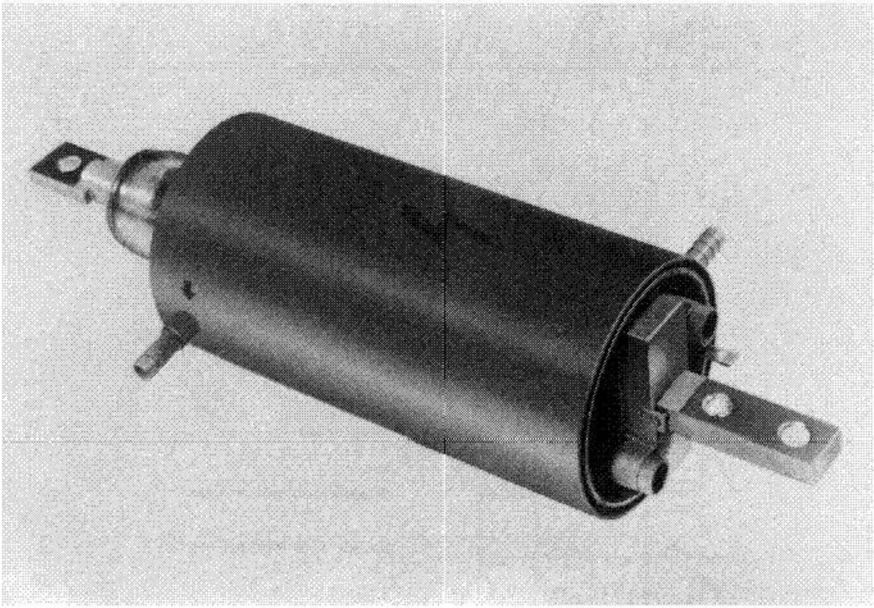


Fig. 5-9. 200 ampere rectifier ignitron.

happen that the igniting rod has become "wetted" by the mercury. This may occur if the tube has carried excessive current, when cathode spots may form on the steel wall of the envelope. Metal may then be vaporised and will ultimately enter the mercury pool, later to be re-evaporated by the arc appearing in each cycle between the ignitor and the mercury pool. The metal will then be deposited on the igniting rod and will form an amalgam with the mercury. A simple method of testing for this condition is to measure the resistance between ignitor and cathode, tipping the tube slightly to withdraw the ignitor slowly from the mercury pool. If the ignitor is in good condition a gradual increase of resistance should take place, but if the ignitor is "wet" the resistance will remain constant for a time, and then suddenly jump to a higher value.

When a tube approaches the end of its useful life it becomes "hard-starting", that is to say a longer and higher current impulse through the igniting electrode is required to start the main discharge. In the firing circuit described above, this defect may be recognised by intense flashing of the thyratrons during each firing operation. Careful supervision of the performance of the equipment will indicate when it becomes necessary to replace a hard-starting tube.

Another tube occasionally used in industrial electronic equipment is the Excitron. This is also a gas discharge tube with mercury-pool cathode, ignition electrode and an auxiliary anode. Unlike the ignitron, however, the ignitor of the excitron is operated only once when the equipment is switched on, the cathode spot thus generated being maintained continuously by the auxiliary anode which is fed from a d.c. source.

Furthermore, the excitron has both an anode and a control grid, so that, the auxiliary discharge once started, it behaves in a similar way to a thyratron. Since the envelope is usually made of stainless steel, the mercury pool cathode is surrounded by a ring of insulating material to prevent the continuously maintained cathode spot approaching the side walls. In addition, special shields and baffles are provided between cathode and anode to render the tube capable of withstanding a high inverse voltage.

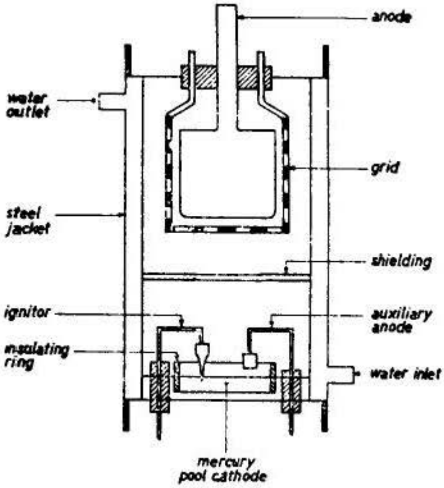


Fig. 5-10. Sectional diagram of an excitron tube.

Excitrons are chiefly employed in rectifiers handling large currents. In many cases, however, ignitrons or multi-anode rectifying valves are preferred, so that the range of application of the excitron in the industrial field is not extensive.

Fig. 5–10 is a sectional diagram of an excitron. The electrical data of this class of tubes are very similar to those of ignitrons and thyratrons, and a fuller description is therefore not necessary.

6. VOLTAGE STABILISING TUBES

Voltage stabilising tubes are gas-filled discharge tubes which can be used for maintaining a voltage at a constant value or for smoothing voltage fluctuations caused by variations of the load or of the mains voltage. They may also be employed as voltage limiters and for generating oscillations of saw-tooth waveform. It will thus be seen that these tubes have a wide field of application in electrotechnics, in radio and television, and in industrial electronics.

The voltage reference tube is a special type of stabilizing tube. It has the advantage of keeping the voltage extremely constant within narrow current limits (a few millivolts only) even after prolonged use, which makes it particularly suitable for providing a reference voltage, for example in stabilizing equipment, thus rendering the use of standard cells superfluous. As a rule voltage reference tubes are designed for currents up to a few milliamperes only.

The special properties of voltage stabilising tubes arise from the shape of the curve relating the voltage across a cold cathode glow discharge and the current flowing through it. This curve is of the form illustrated in fig. 6–1.

If a direct voltage of a certain critical value (known as the "ignition voltage",

V_{ign}) is applied between the cathode and anode of the tube, the electrons emitted by the cathode (negative electrode) attain sufficient speed to ionise any gas atoms with which they may collide. The positive ions thus produced are attracted to the cathode, which they strike with sufficient force to liberate further electrons. Eventually a continuous discharge is set up. If, now, the current through the tube increases, the amount of ionisation also increases to a point at which the discharge can be maintained by primary electrons travelling at much lower speeds, that is to say the voltage across the tube necessary to maintain the discharge is reduced to a value known as the "operating voltage". Further increase of current through the tube involves only a small increase of the voltage across the tube, this is mainly the voltage drop occurring between the cathode and a positive ion space charge.

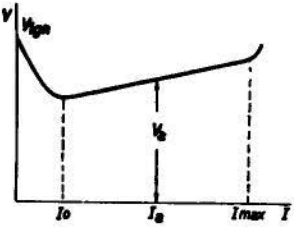


Fig. 6-1. Voltage-current diagram of a cold cathode glow discharge.

It is upon this fact — that over a given range of current values the voltage across the tube is substantially constant — that the operation of the voltage stabiliser is based, the actual value at which the voltage is stabilised being the average value (V_a) of the operating voltage. It should be stated, however, that if the current is increased beyond a certain value I_{max}, the voltage rises again and the nature of the glow discharge changes to an arc discharge. Under this condition, the heat generated by the rapidly increasing current damages the tube, and it is therefore essential that a protective resistor of suitable rating be connected in series with the stabiliser tube unless the voltage source has a sufficiently high internal resistance to limit the tube current to a safe value.

It will be obvious that the flatter the curve between the points I_0 and I_{max} in fig. 6–1, the more accurate will be the stabilising effect. If this part of the curve is assumed to be linear, it may be described by the equation:

$$V = V_a + \Delta I \cdot R. \tag{6.1}$$

R is the so-called a.c. resistance and is:

$$R = \frac{\Delta V}{\Delta I}. \tag{6.2}$$

Obviously a small value of R is desirable for good stabilisation.

Fig. 6–2 is the basic circuit for stabilising a direct voltage which is subject to fluctuations. It is, of course, essential that the supply voltage V_b is greater than the ignition voltage of the stabiliser tube. If V_b changes by an amount $\pm \Delta V_b$, there will be a corresponding change in the current through R_1; but since the voltage V_a across the tube is practically constant and independent of the current through the tube, the whole of the variation in V_b will appear across R_1. The change in the current through R_1 is therefore:

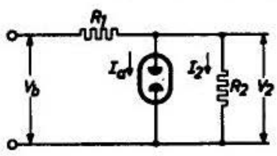


Fig. 6-2. Basic voltage stabilising circuit.

$$\Delta I = \frac{\Delta V_b}{R_1}. \tag{6.3}$$

Because the voltage across the load R_2, and thus the current I_2 flowing through it, are practically constant, the change ΔI in R_1 is almost entirely carried by the tube, so that the nett voltage change across the load is, according to equation (6.1):

$$\Delta V_2 = \Delta I \cdot R = \frac{R}{R_1} \cdot \Delta V_b. \tag{6.4}$$

In order to ensure good stabilisation, R_1 should therefore be as large as possible. However, an upper limit is imposed for R_1 by the minimum current I_0 required to maintain the discharge (see fig. 6–1). The following condition must therefore be fulfilled:

$$V_b - \Delta V_b - V_a \geqq R_1 (I_0 + I_2), \tag{6.5}$$

or

$$R_1 \leqq \frac{V_b - \Delta V_b - V_a}{I_0 + I_2}. \tag{6.6}$$

A further limitation is imposed by the necessity of ensuring that ignition of the tube can occur. When the tube is non-conducting, the supply voltage V_b appears across the resistors R_1 and R_2 in series, and care must be taken that the part of this voltage appearing across R_2 is greater than the ignition voltage V_{ign}. The following condition must therefore be satisfied:

$$\frac{V_b - \Delta V_b}{R_1 + R_2} \cdot R_2 > V_{ign}, \tag{6.7}$$

or, with

$$R_2 = \frac{V_a}{I_2},$$

$$R_1 < \frac{(V_b - \Delta V_b - V_{ign})\, V_a}{V_{ign}\, I_2}. \tag{6.8}$$

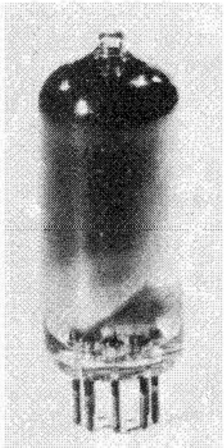


Fig. 6-3. Philips 85A2 voltage reference tube.

Experience shows that a lower limiting value of R_1 results from condition (6.8) than from condition (6.6). This means that, due to tube ignition requirements, the stabilising effect obtained is less than that which would be possible if R_1 could be chosen solely by consideration of the minimum tube current requirement.

Finally R_1 must be chosen with due regard to the maximum permissible current I_{max} through the tube. If the supply voltage changes from $V_b - \Delta V_b$ to $V_b + \Delta V_b$, the current through the tube increases, but must not be allowed to exceed the value I_{max}. Since the voltage across R_2, and thus the value of I_2 are practically constant, the following condition must be satisfied:

$$R_1 \geqq \frac{V_b + \Delta V_b - V_a}{I_{max} + I_2}. \tag{6.9}$$

This gives the lower limit for the series resistor R_1.

The following calculation for a practical case will serve by way of example. Let it be assumed that a stabilised direct voltage of 85 volts at a load current of 2 milliamperes is required, and that the nominal mains voltage of 200 volts is subject to fluctuations of ± 15% — a percentage fluctuation which is quite typical of present-day conditions. Further, let it be assumed that a voltage reference tube Type 85 A2 is selected *). This tube, which is illustrated in fig. 6-3 has the following characteristics:

Operating voltage (V_a)	85 V
Ignition voltage (V_{ign})	125 V
A.C. resistance (R) (average value)	300 Ω
Maximum tube current (I_{max})	10 mA
Minimum tube current (I_0)	1 mA

According to condition (6.6):

$$R_1 \leqq \frac{200 - 30 - 85}{1 + 2} = 28 \text{ k}\Omega,$$

However, according to condition (6.8):

$$R_1 < \frac{(200 - 30 - 125) \times 85}{125 \times 2} = 15.3 \text{ k}\Omega,$$

and according to condition (6.9):

$$R_1 \geqq \frac{200 + 30 - 85}{10 + 2} = 12.1 \text{ k}\Omega.$$

A value of 15 kΩ for R_1 will therefore be chosen, and the fluctuation of the output voltage, ΔV_2 will be, according to equation (6.4).

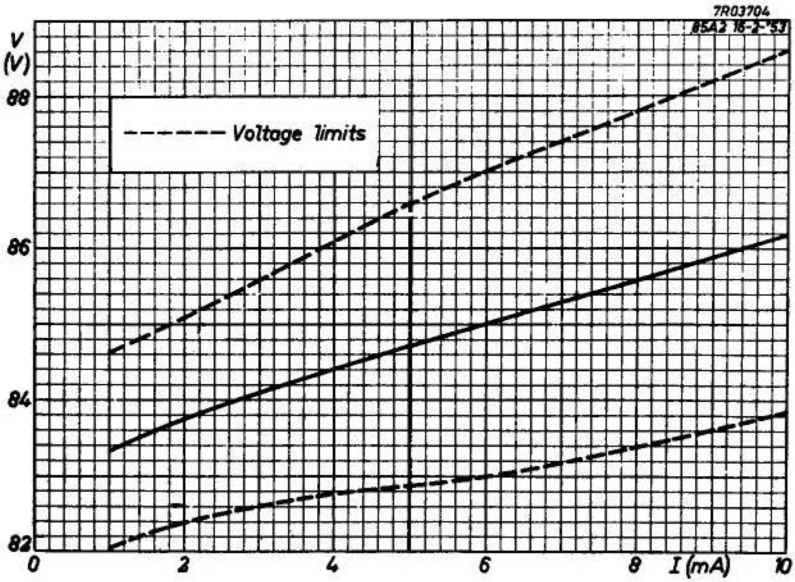


Fig. 6-4. Voltage-current characteristic of the 85 A2 stabilising tube.

*) Instead of the voltage reference tube 85 A2 a voltage stabiliser such as the 90 C1 can be used if the requirements imposed on the voltage stability are not too stringent.

$$\Delta V_2 = \frac{300 \times 30}{15\,000} = 0.6 \text{ V.}$$

It is thus seen that a variation of about $\pm$ 15% in the input voltage results in a change of only about $\pm$ 0.7% in the output voltage across the 85 A2 tube.

If a higher stabilised voltage than that according to the operating voltage of a given tube is required, two or more stabilising tubes may be connected in series. The overall characteristic of such a combination can be calculated by adding the voltages across the several tubes for the appropriate current, while the overall a.c. resistance is, of course, the sum of the a.c. resistances of the individual tubes.

The voltage required for igniting such a chain of tubes need not, however, be the sum of the ignition voltages of all the tubes. If, as shown in fig. 6–5, one of the tubes is by-passed by a resistor R_3 of high value, the remaining two tubes will ignite first, after which a voltage equal to twice V_a appears across them, and the remaining part of the input voltage suffices to ignite the by-passed tube.

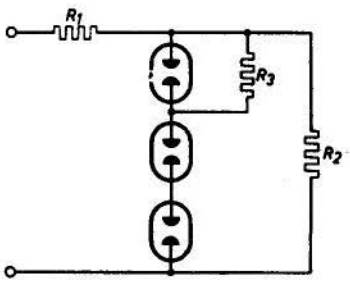


Fig. 6-5. Series connection of stabilising tubes

When it is desired to stabilise the voltage between very close limits, the multiple stabiliser circuit shown in fig. 6–6 may be employed. Here, tubes *I* and *II* produce a certain degree of stabilisation so that a substantially constant current flows through tube *III* which, in turn, finally stabilises the voltage appearing at the slider of the potentiometer. The stabiliser Type 85 A2 is particularly suitable for this appli-

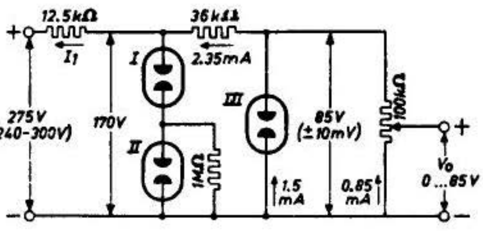


Fig. 6-6. Multiple stabilising circuit.

cation, and using three such tubes in the circuit shown, the fluctuations in V_o are only $\pm$ 0.005% for a $\pm$ 10% variation of the input voltage.

It should be mentioned that it is not permissible to connect stabiliser tubes in parallel in order to operate at a higher current. In such circumstances tubes having a larger current range must be used.

Voltage stabilising tubes are occasionally used for generating saw-tooth oscillations. The basic circuit is shown in fig. 6–7. The tube is connected to a direct voltage source via the series resistor R_1, and is also shunted by the capacitor C. The capacitor charges via R_1 until the voltage across C is equal to the ignition voltage of the tube, when the tube ignites and the capacitor discharges; the initial value of the discharge current corresponding to point 2 on the tube characteristic is also reproduced in fig. 6–7. The voltage across the capacitor there-

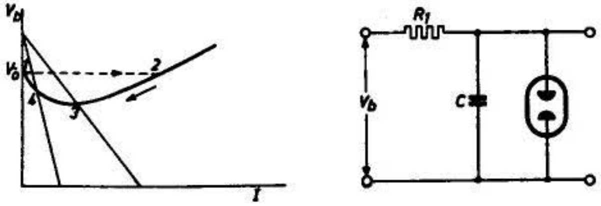


Fig. 6-7. Saw-tooth oscillator circuit.

fore decreases, and so does the discharge current. The value of the voltage follows the curve from point 2 towards the point 3. At the same time, however, current also flows from the supply source to the capacitor through R_1, thus charging it once more.

If the discharge current through the tube is equal to the charging current through R_1, a condition of equilibrium is set up so that the voltage across the capacitor becomes constant, and no oscillations will be generated. This will be the case if the line corresponding to the equation:

$$v = V_b - IR_1 \qquad (6.10)$$

intersects the curve at the point 3. If, however, the value of R_1 is sufficiently high, the intersection will be at some such point as 4, the charging current via R_1 will be less than the discharge current through the tube, and the voltage across C will continue to fall until the tube is extinguished. The capacitor will then charge up again to the value of the ignition voltage, and the cycle repeats. To make the circuit operative, therefore, the value of R_1 must be so chosen that the intersection of the line and the tube characteristic curve falls on the left-hand side of the lowest point of the curve.

In electronic regulators, where some variable physical quantity, such as a pressure, temperature, velocity etc., is represented by a voltage, a very constant reference voltage is required for the purpose of comparison. Such a constant voltage can be obtained by using voltage reference tubes, such as Philips Type 85 A2. This tube has a cathode of pure molybdenum, and in order to avoid damage to the cathode surface and contamination of the gas filling, the inner surface of the glass envelope is coated with a layer of molybdenum. This coating serves as a screen between the bulb and the gas discharge, ensuring high stability of the operating voltage throughout life.

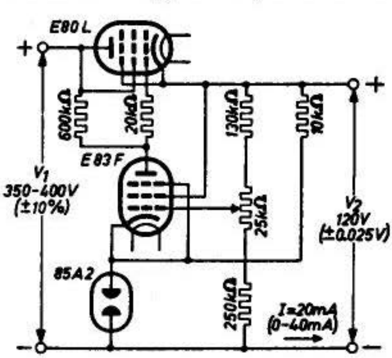


Fig. 6-8. Voltage stabilising circuit using an 85A2 reference tube.

Fig. 6–8 is the basic circuit for this application, the 85 A2 being used as a voltage reference tube. Its operation is as follows: Increase of the input voltage V_1 causes a corresponding increase of the output voltage V_2, so that the control grid of the E 83 F pentode, which is fed from a potentiometer across V_2 becomes more positive. The anode current of the E 83 F therefore rises, and the potential at its anode and thus at the control grid of the power pentode E 80 L decreases. The voltage drop across the E 80 L therefore increases, thus tending to stabilise the value of the output voltage V_2.

The effectiveness of the stabilising process depends upon the constancy of the potential at the cathode of the E 83 F, and it is the function of the 85 A2 to ensure the constancy of this reference voltage.

The maximum current output of this circuit is determined by the maximum permissible anode current of the E 80 L. Higher outputs may be obtained by using a power tube of higher anode current rating.

When using voltage stabilising tubes it is important to remember that the electrodes have been polarised in the course of manufacture. The electrode marked "Anode" must therefore always be connected to the *positive* terminal of the voltage source.

7. PHOTOCELLS

During recent years the practical applications of the photoelectric cell, or photocell as it is more usually termed, have greatly multiplied. In addition to their familiar use in sound-film equipment, they are now employed in a wide variety of devices for automatic control, signalling and warning, particularly in connection with counting, and checking the uniform quality of finished products. They are also used in alarm and protective circuits in banks, museums, shops, offices and so forth.

Photocells are diode tubes consisting of an anode and a cathode sealed into a glass envelope which is either highly evacuated or gas-filled. Unlike that of the thermionic diode, the cathode of a photocell is photo-emissive, that is to say it emits electrons when irradiated by light. The cathode is usually semi-cylindrical in form, while the anode is usually a single wire situated approximately at the centre of the half-cylinder. The chemical structure of the photo-emissive cathode is rather complex, and usually consists of a layer of pure silver on which is deposited a thin layer of the oxide of one of the alkaline metals such as caesium, throughout which there is distributed a certain quantity of the free atoms of the metal.

When light falls upon such a cathode, the free atoms are ionised, electrons being liberated. These electrons then move towards the positive anode. The amount of light energy required to ionise a given atom depends upon the location of that atom with respect to its neigbouring atoms.

Owing to the random nature of the structure of a photo-emissive cathode, its sensitivity is not uniform over its whole surface. If, however, the light beam operating the cell is made divergent by means of a suitable lens, so that the whole of the cathode surface is irradiated, the cell will operate at a constant mean sensitivity. Errors due to the non-uniform distribution of the free atoms over the cathode surface cancel each other out, and furthermore, the risk of local overloading of the cathode will be avoided.

The spectral response of a photocell depends upon which alkali metal is employed in the cathode. For example, caesium cathodes have a maximum sensitivity when irradiated with light having wavelengths between 7000 Å and 9000 Å, that is to say in the red and infra-red region of the spectrum as shown in fig. 7–1. Such cells are usually preferred in industrial devices since their spectral response corresponds to the more commonly used sources of

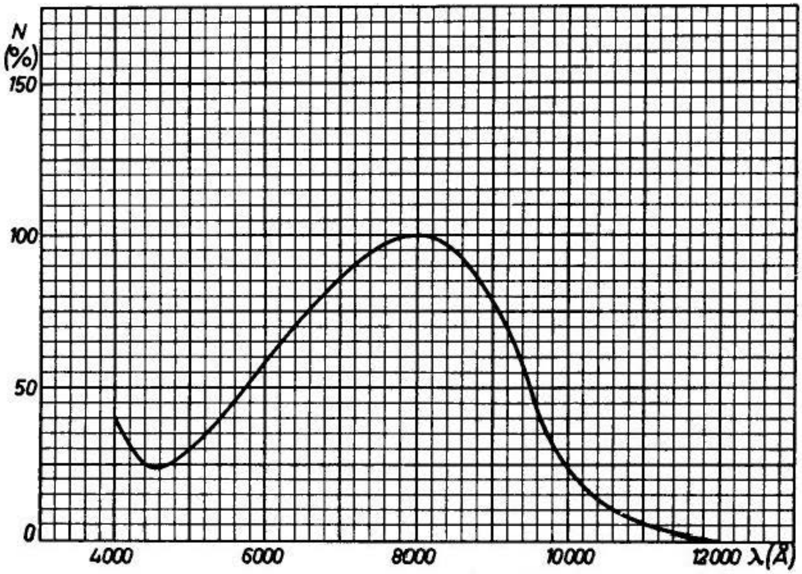


Fig. 7-1. Spectral response curve of a photocell with caesium cathode.

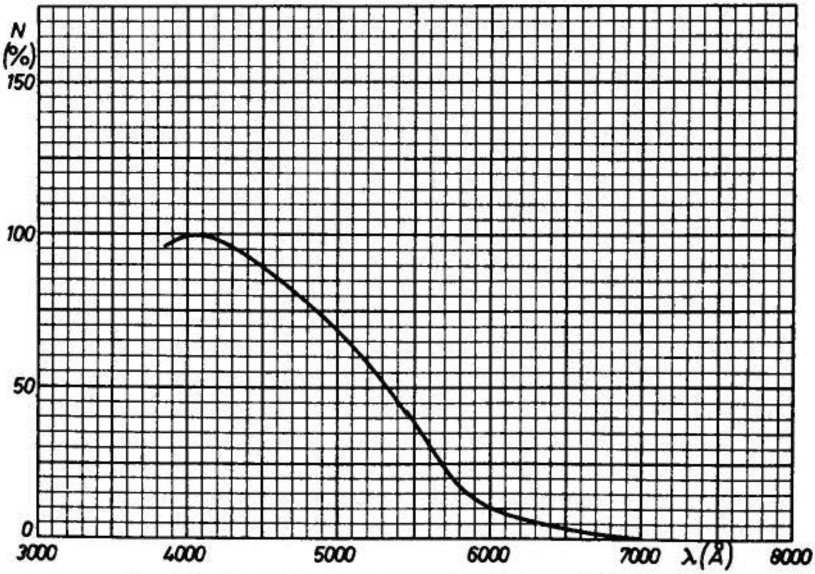


Fig. 7-2. Spectral response curve of a caesium-antimony cathode.

illumination. A very good blue-sensitive cathode is the caesium-antimony cathode. As seen from the spectral response curve reproduced in fig. 7–2, the greatest sensitivity of the caesium-antimony cathode is the range of wavelengths between 3800 Å and 4500 Å, that is to say for violet and blue light. Ultra-violet rays which have wavelengths below 3850 Å are absorbed by the glass envelope of the tube, so the curve does not continue below this value. If photo-cells sensitive to ultra-violet radiations are required the bulb must be provided with a quartz window through which these rays may pass and reach the cathode.

The maximum permissible cathode current for a particular type of tube is specified in the published data, and is the maximum permissible current when the entire cathode surface is uniformly illuminated. If, however, the operating conditions are such that only a part of the cathode surface is illuminated, the cathode current must be correspondingly reduced.

Even when a photo-cathode is not illuminated it will emit a small number of electrons, the emission depending upon the ambient temperature. The "work function" of the cathode surface is so low that even at room temperature some thermionic emission is observed. This "dark current" is, however, very small, being of the order of 10^{-8} amperes per square centimeter for a caesium cathode. For normal industrial applications, therefore, the dark current can usually be neglected since fairly high light intensities will be used, so that the ratio of photo emission to dark current will be large. Only in very sensitive apparatus where great accuracy is required will the dark current introduce appreciable errors, but this can be corrected by compensating circuitry.

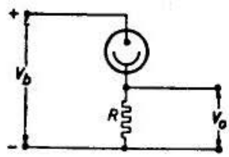


Fig. 7-3. Basic circuit of a high-vacuum photocell.

In the basic circuit reproduced in fig. 7–3, a high-vacuum photocell is connected in series with a resistor R. If a sufficiently high positive potential (approximately 80 volts) is applied to the anode, all the electrons emitted by the cathode will pass to the anode. Further increase of the anode voltrage does not result in any increase in the tube current — in other words the tube operates as a saturated diode.

This is shown in the characteristic curve, fig. 7–4. If, however, the voltage applied to the anode is less than the saturation value, not all the electrons emitted by the cathode will reach the comparatively small anode, a proportion of them returning to the cathode, so that the value of the anode current is smaller than the saturation current, i.e. the sensitivity of the tube is reduced. To obtain full sensitivity, the photocell should be operated at an anode voltage of between 90 and 100 volts.

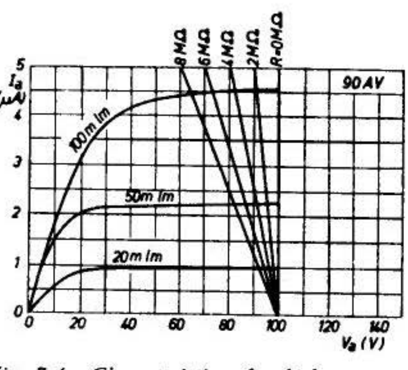


Fig. 7-4. Characteristics of a high-vacuum photocell with load lines.

The sensitivity of vacuum type photocells is somewhat low — in the order of 20 to 40 micro-amperes per lumen. If, however, the tube contains a small quantity of an inert gas, the sensitivity will be considerably increased by "gas amplification", which may be explained as follows. When electrons pass from the cathode to the anode in a gas-filled tube, a proportion of them will collide with the gas atoms. If the velocity of the electrons is low, such collisions will not affect the anode current, but if the electrons have traversed a potential which exceeds the ionisation voltage of the gas, they will have attained sufficient momentum to ionise the gas atoms with which they collide. This means that at each collision a positive ion is produced which moves towards the cathode, and a free electron is released which, together with the original electron, moves towards the anode. These two electrons may now ionise further gas atoms, so that for one electron emitted from the cathode, several electrons ultimately reach the anode. Moreover, the positive ions reaching the cathode strike it with sufficient force to release further electrons, and these, in their turn, ionise further gas atoms. It will be clear that by this process, the original photo-electric current is considerably amplified, and that the gas amplification factor increases with the tube voltage since the velocity of the electrons is directly proportional to the voltage gradient traversed.

There is, however, an upper limit beyond which the anode voltage may not be increased. Excessive voltage will result in the setting up of a glow discharge across the tube; the anode current is then limited only by the value of the series resistor, and may reach a value at which the bombardment of the cathode by positive ions results in damage to the photocell. Care must therefore be taken that the maximum voltage specified by the tube manufacturer is never exceeded. Since the ignition voltage of gas-filled photocells ranges from about 100 volts to 150 volts according to type, the maximum permissible anode voltage is usually in the order of 75 to 100 volts. The gas amplification factor obtainable is in the region of 5 to 10.

A typical I_a–V_a characteristic of a gas-filled photocell is shown in fig. 7-5. Over the curved parts of the characteristic the voltage developed across the load resistor R will not be exactly proportional to the amount of light falling on the cathode. Gas-filled photocells are not, therefore, very suitable for applications in which very accurate measurements are required. They are, however, very suitable for sound reproduction in sound-film equipment because, with load resistors of values normally used in this application, distortion due to the non-linearity of the characteristic is negligible.

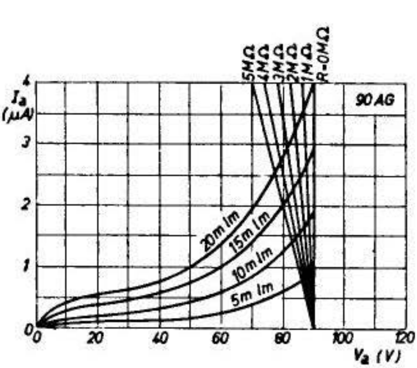


Fig. 7-5. Typical I_a–V_a characteristic of a gas-filled photocell with load lines.

Gas-filled photocells are also usually preferred for those industrial applications in which great sensitivity is more important than strictly linear response. The sensitivity of gas-filled cells normally ranges up to about 150 micro-amperes per lumen.

It is now necessary to consider the behaviour of a gas-filled photocell when the light falling upon the cathode is subject to very rapid fluctuations. It is found that, at the higher frequencies, the gas amplification decreases. This is because the positive ions resulting from the ionisation of the gas are so much heavier than the electrons that their velocity is relatively low. When, therefore, the light is suddenly interrupted, there are still some ions reaching the cathode and these release new electrons capable of ionising further gas atoms. The number of newly formed positive ions is, however, insufficient to maintain the anode current at its original value, and the current will therefore decrease.

Similarly, the anode current will not reach its final value immediately the illumination of the cathode is restored. This means that at the higher frequencies the response of the cell is unable to follow the light fluctuations, and at frequencies above 1000 c/s the amplification begins to fall off. However, this decrease of sensitivity is not serious for frequencies below 10 kc/s, so that over this frequency range the variation in amplification does not sensibly affect practical applications.

When using photocells it must be borne in mind that the photo-electric current is in the order of a few micro-amperes only. Good insulation of the tube socket

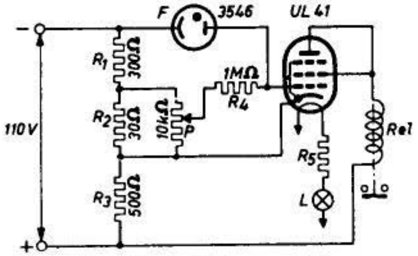


Fig. 7-6. Simple light-controlled relay circuit.

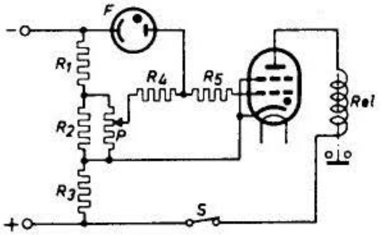


Fig. 7-7. Relay circuit using a thyratron.

and of the wiring is therefore essential in order to avoid leakage. Where a very large load resistor, or a high gain in the following amplifier is necessary, careful screening of the cell and of the wiring is recommended. In addition, care should be taken that the ambient temperature does not exceed 50 °C, otherwise the cathode emission may decrease, and thus the sensitivity of the tube. The sensitivity will also decrease temporarily if the cell has been exposed to very intense illumination, for example direct sun-light, even if no anode voltage was applied. The possibility of this must be considered in installing photocell equipment.

A circuit for a simple light-controlled relay is given in fig. 7–6. It uses a gas-filled photocell, and an amplifying pentode Type UL 41. A voltage divider consisting of het resistors R_1, R_2 and R_3 is connected across the 110 volt d.c. supply, R_3 being at the positive end of the chain. The voltage across R_3 is applied between the cathode and anode of the UL 41 via relay *Rel*, and the control grid of the pentode receives an adjustable negative bias via potentiometer *P*. The photocell *F* (Philips Type 3546) obtains its anode voltage from the voltage appearing across R_1.

If the cathode of the photocell is illuminated, the photo-electric current flowing through R_4 produces a voltage drop of such a value that the UL 41 is almost cut off. If, now, the light falling upon the cell is interrupted, the photo-electric current ceases, so that the negative control grid voltage falls, and the anode current of the UL 41 increases and energises the relay, closing the main control circuit. Obviously the relay will open again if light once more falls upon the cell.

In applications such as alarm devices, in which it is desired that the alarm circuit closes on interruption of the light beam and remains closed until the circuit is opened by hand, even if the light beam is restored after a short interval, a special type of relay may be used. But a simpler solution is to use a small thyratron in place of the power pentode. The circuit for this arrangement is shown in fig. 7–7, and differs but little from the previous circuit.

As explained in an earlier chapter, a thyratron, once ignited, remains conductive until extinguished by reducing the anode voltage to a value less than the arc voltage, or even to zero. Thus, in the circuit shown in fig. 7–7, the thyratron, having been ignited by the action of the photocell, will remain conductive so that relay *Rel* continues to be energised until switch *S* is opened, even if the cell is illuminated again.

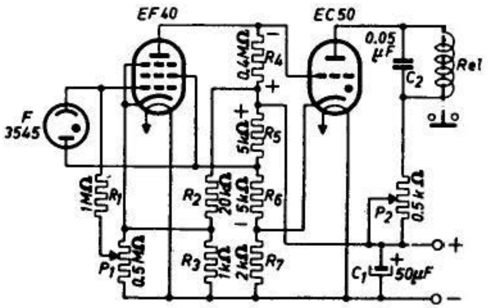


Fig. 7-8. Light-controlled relay circuit with pre-amplifier stage.

Where a vacuum type photocell is preferred or where the amount of light falling on the cell is very small, a pre-amplifier stage should be interposed between the photocell and the relay tube, as shown in fig. 7–8. The voltage amplifying pentode EF 40 receives a negative control grid bias from potentiometer P_1 as before. If the photocell *F* is illuminated, the grid potential becomes less negative, and the EF 40 passes current, thus producing a voltage drop across resistor R_4 with the polarity indicated. The grid of the gas triode EC 50 is thus driven negative, and this tube is cut off (see note on page 30). If now the light beam falling upon photocell *F* is interrupted, the grid potential of the EF 40 becomes more negative, the anode current of the EF 40 falls and the potential at the grid of the EC 50 is driven positive causing the tube to ignite and energise the relay.

In this circuit, of course, the gas triode will extinguish and become non-conducting, thus de-energising the relay as soon as the photocell is once more illuminated, since the positive ions will be neutralised by the increasing negative voltage on the grid of the EC 50. If it is desired that the relay should remain energised, the gas triode EC 50 should be replaced by a suitable thyratron such as Philips Type PL 2D 21.

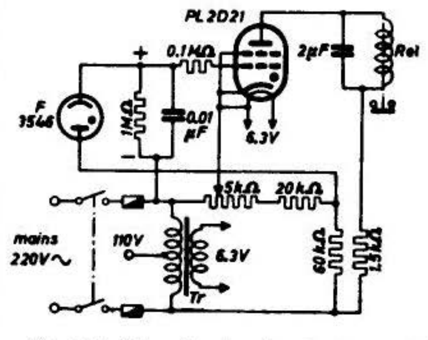


Fig. 7-9. Photoelectric relay circuit operated by a.c. supply.

A somewhat similar circuit, operated from an alternating current supply, is shown in fig. 7–9. Both the thyratron and the photocell are fed from the a.c. supply, but since these tubes do not operate during negative half cycles the response may be delayed by a maximum of 1/100 second. The circuit is so designed that the thyratron ignites, energising relay *Rel*, when light falls upon the photocell. By a slight modification of the circuit, however, the reverse

Fig. 7-10. (left) Gas-filled photocell with caesium cathode.

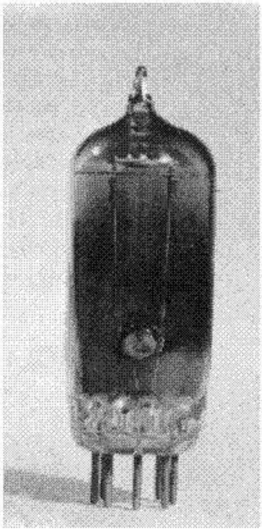


Fig. 7-11. (right) Modern high-vacuum photocell with caesium-antimony cathode.

operation can be obtained, that is to say the relay is energised when the light beam is interrupted.

Fig. 7–10 shows a typical gas-filled photocell with caesium cathode sensitive to red and infra-red light, and in fig. 7–11 is seen a modern high-vacuum cell with caesium-antimony cathode, sensitive to the blue region of the spectrum.

8. TRIGGER TUBES

The name "trigger tube" is sometimes applied to all those forms of gas discharge tube which may serve as relays for starting a process by means of a comparatively small signal. Thus thyratrons, senditrons and the like are sometimes called "trigger tubes". In this book, however, "trigger tube" is reserved for one particular class of tube, namely cold cathode thyratrons, which are particularly suitable for this type of application. An important advantage of the cold cathode thyratrons is that, as they require no cathode heater supply, they are ready for instantaneous operation at all times. They are therefore often used in signalling and controlling equipment which must always be ready for immediate service.

A cold cathode thyratron contains a specially prepared cathode, a main anode and an auxiliary anode or "starter", all sealed into a gas-filled bulb. If a positive potential of a certain value (the ignition voltage) is applied to the starter, electrons are emitted from the cathode and ionise gas atoms by collision. The positive ions thus produced bombard the cathode and release further electrons, and if a positive potential is applied to the anode the main discharge between cathode and anode is set up.

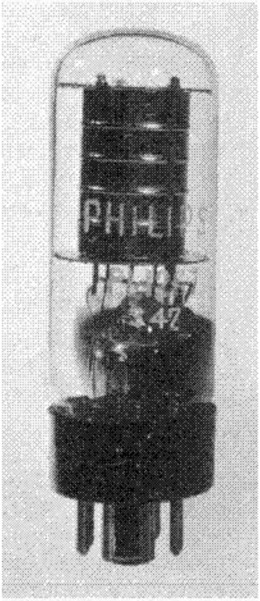


Fig. 8-1. Philips PL 1267 trigger tube.

The voltage drop between cathode and anode is then practically independent of the value of the anode current, so that the anode current is governed only by the applied anode voltage and the resistance in the external circuit. The circuit must therefore be so designed that the anode current can never exceed the maximum rated value specified in the tube data.

The main advantages of the trigger tube are as follows:

(1) As already stated, the tube is always ready for instant operation, and requires no warming-up time.
(2) It consumes no energy when not operating — a matter of particular importance if the equipment is fed from batteries.
(3) There is no wear and tear on the tube unless during operation, and so a long working life may be expected.
(4) The auxiliary voltage required to ignite the tube does not depend upon the value of the anode voltage.

A typical trigger tube, Philips Type PL 1267, is illustrated in fig. 8–1. This tube is rated for an average anode current of 25 milliamperes, so that a relay having a coil wound for this current may be connected in the anode circuit. However, as the useful life of the tube largely depends upon the average load current, it is advisable to operate the tube at a current somewhat less than the maximum rated value.

The behaviour of a trigger tube under any operating conditions can be ascertained from its ignition characteristic, which is always of the form indicated in fig. 8–2. At any combination of anode and starter voltage within the closed loop no discharge will occur if the boundary of the curve has not been crossed previously. If, however, the tube is subjected to conditions corresponding to a point upon the curve itself or outside the loop, a discharge will be initiated and will be maintained even if the conditions are changed to values corresponding to some point within the loop, the particular electrodes involved in the discharge and the direction of the discharge depending upon the values of the anode and starter voltages when the discharge is initiated.

Thus, section *a* of the loop corresponds to a discharge between starter and cathode (direction of *positive* current). It is seen that the ignition voltage is independent of the value of the anode voltage.

A discharge from anode to cathode occurs when conditions corresponding to a point on section *b* of the curve are applied. Section *c* corresponds to a discharge from anode to starter; section *d* to a discharge from cathode to starter;

section *e* to a discharge from cathode to anode; and section *f* to a discharge from starter to anode.

As, however, the potentials V_a and V_{ah} applied to the anode and the starter respectively are usually both positive, the tube will normally operate in quadrant *I* of the closed loop.

The basic circuit of a light-controlled relay which may be operated direct from the 110 volt a.c. mains is shown in fig. 8–3. This circuit is particularly suitable for warning or signalling equipment which must remain ready for operation over a period of several years without maintenance. A similar device may be used for such purposes as the automatic switching of street lighting, the lighting of business premises and so forth, where the apparatus has to be installed in

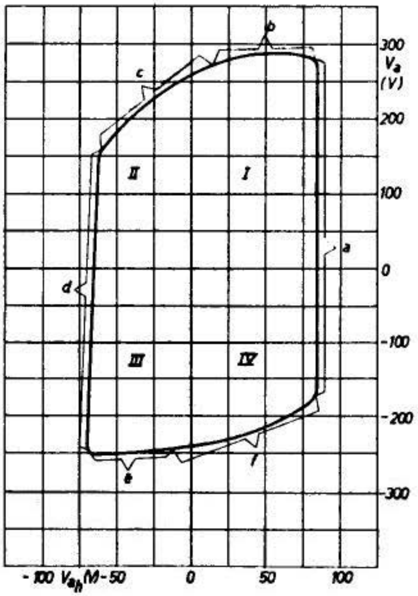


Fig. 8-2. Ignition characteristic of a trigger tube.

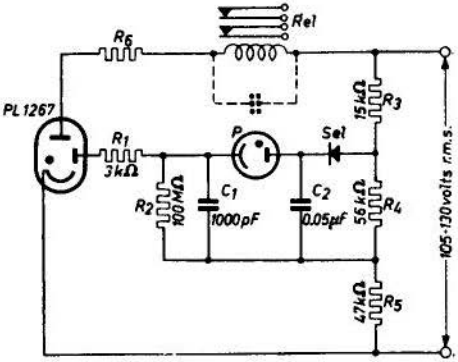


Fig. 8-3. Basic circuit of a light-controlled relay using a trigger tube.

inaccessible positions such as on the roof, chimneys etc.

The operation of this circuit is as follows: Capacitor C_2 is charged via selenium rectifier *Sel* to a voltage which is applied via resistor R_2 to the photocell *P* — which should preferably be of the gas-filled type. When the photocell is illuminated, the photo-electric current produces a voltage drop across R_2, a positive potential appearing at the upper end of the resistor. This positive direct potential, added to the alternating voltage drop across R_5, is applied to the starter of the trigger tube Pl 1267 via R_1, and causes the tube to fire during every positive half cycle. Resistor R_6 is a limiting resistor of sufficient value to prevent the anode current of the trigger tube exceeding the maximum permitted value. It is advisable to shunt the relay coil by a capacitor of from 1 to 2 μF to prevent the relay fluttering by reason of the intermittent nature of the anode current.

A variant of this circuit, in which the trigger tube is ignited if the light continuously falling upon the photocell is interrupted, is shown in fig. 8–4.

By using a suitably designed potential divider or a transformer, these circuits may be operated from 220 volt a.c. mains. If a direct current supply is available the circuits may also be used as alarm devices. In this case, however, once ignited, the trigger tube remains conductive, and the circuit has to be opened by hand. If this is not convenient, a gas triode may be substituted for the trigger tube; the circuit will then be interrupted when the grid of the gas triode is made negative.

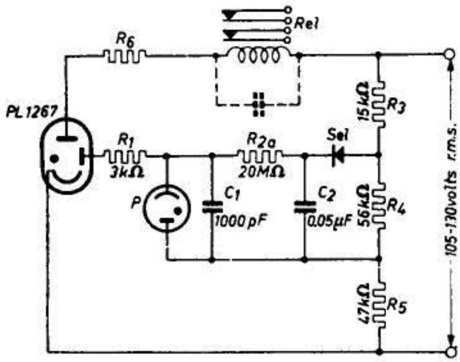


Fig. 8-4. Variant of the circuit shown in fig. 8-3.

A very interesting application of the trigger tubes is in "ring" counter circuits for counting impulses. These circuits may form part of such devices as electronic computors. The basic circuit is given in fig. 8-5. If switch *A* is closed, a positive potential which is, however, insufficient to cause ignition, is applied to the first trigger tube V_1. If, now, a positive impulse is superimposed on the auxiliary electrode potential, V_1 ignites, and a positive potential due to the discharge

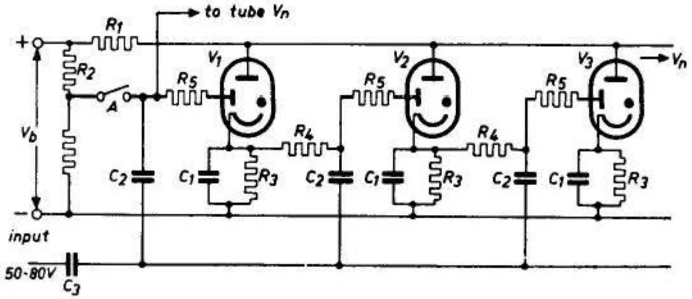


Fig. 8-5. Basic circuit of a counting circuit.

current flowing through R_3 is applied to the auxiliary anode of V_2, but again is of insufficient value to cause ignition. If, however, switch *A* is re-opened and a second positive pulse is applied to the circuit, V_2 will ignite, thus increasing the current through R_1 and the voltage drop across it. Because at that instant capacitor C_1 still holds its charge, the voltage across V_1 is reduced below the operating voltage and V_1 will be extinguished. Similarly, a third impulse will fire V_3, since this is now the only tube having a positive bias, and simultaneously V_2 will be extinguished. This process will continue until the n^{th} pulse fires V_n.

In fig. 8-6 the n^{th} stage of the counter circuit is shown, and it will be seen that the n^{th} tube provides the positive bias for the first tube, V_1, so that the $(n + 1)^{\text{th}}$ pulse fires V_1 again, thus closing the ring. Another operation of switch *A* is therefore not necessary. The $(n + 1)^{\text{th}}$ pulse simultaneously fires tube V_{n1}, which forms the input to the next counter circuit. This tube passes current only while capacitor C_4 discharges, and becomes non-conductive before C_4 can recharge via resistor R_6. In this way a positive voltage pulse appears across resistor R_8, causing ignition of the first tube in the second ring of the counter circuit. Further impulses applied to the circuit will cause the tubes of the first ring to fire again in succession until the $(2n + 1)^{th}$ impulse fires the second tube of the second ring counter circuit via V_{n1}.

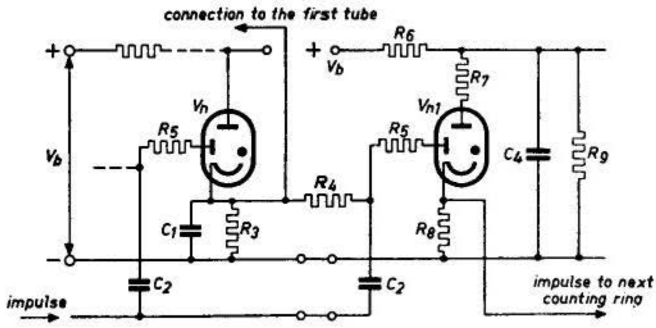


Fig. 8-6. Circuit of the n^{th} stage of the ring counter circuit.

The whole or a part of the resistors R_3 may consist of suitable relays, signal lamps or the like which can indicate the number of pulses counted.

If, in fig. 8–5, the resistor R_1 and the capacitors C_1 are omitted, the preceding tube will remain conducting after every impulse until, after n impulses, all the tubes in the first counter ring are ignited. In this arrangement, which also has practical applications, the anode voltage line has to be interrupted shortly after each complete cycle, thus extinguishing all the tubes. This can be done, for example, by a relay operated by tube V_{n1}.

9. CATHODE-RAY TUBES

Although the cathode-ray tube is seldom employed in electronic industrial control equipment, it is an essential component of a most important instrument — the cathode-ray oscilloscope — which is widely used for measurement and for checking and maintaining industrial electronic devices. It is for this reason that a description of the cathode-ray tube is included in this chapter.

Briefly described, a cathode-ray tube is a thermionic tube in which electrons, emitted from an indirectly-heated cathode located at one end of the tube, are focused into a convergent beam which, impinging on a luminescent screen at the other end of the tube, produces a light spot at the point of impact. By deflecting the electron beam simultaneously in the vertical and horizontal directions, the light spot can be moved to any point on the screen. If the horizontal deflection of the spot is made, say, a linear function of time, and the vertical deflection is made proportional to the instantaneous values of a variable voltage which it is desired to examine, then the light spot will trace on the screen a graph showing the voltage under examination as a function of time.

In the cathode-ray tube, free electrons are emitted from an indirectly-heated cathode, the actual emissive area of which is very small. Surrounding the cathode is a small cylindrical electrode to which is applied a negative biasing potential.

Its main function is to control the intensity of the electron beam. Since this function is analogous to that of the control grid of an amplifying tube, this electrode is also termed the "grid".

The electrode assembly, known collectively as the "gun", also includes two electrodes to which positive potentials are applied. These electrodes, which are usually hollow cylinders or discs with a central aperture, not only accelerate the electrons in the direction of the screen, but also focus the beam into a narrow pencil. This is achieved by the form of the rotation-symmetrical electric field produced by these electrodes. Since the effect of this field upon the electron stream is similar to that of an optical lens upon a beam of light, this part of the electrode system is commonly termed an "electron lens". Correct focusing of the beam on to the luminescent screen is obtained by adjusting the potentials applied to the focusing electrodes.

In order to obtain a sharp, bright trace upon the screen, the positive potential at the final anode must be high, so that the electrons attain a high velocity. The electrons forming the beam mutually repel each other, so that the beam tends to diverge. If, however, the velocity of the electrons is sufficiently great, the electrons will reach the screen before their mutual repulsion has resulted in serious defocusing.

Deflection of the electron beam can be effected in two ways — by means of electric fields applied between pairs of plates within the tube, or by magnetic fields produced by a coil system outside the tube. The second system has the advantage that deflection over a wide angle can be attained so that the overall length of the tube can be comparatively small. It is for this reason that the picture tubes used in television receivers are always arranged for magnetic deflection, since for this service large pictures are required. Furthermore, the focusing of the electron beam in these tubes is usually also achieved by a magnetic field. Magnetic deflection, however, becomes ineffective at high frequencies, and, moreover, requires rather complicated circuitry. Therefore the electron beam in cathode-ray tubes used for oscilloscopes is always electrostatically deflected. Since generally much smaller images are required in oscilloscopes, a deflection angle of about 20° suffices; and this can be easily obtained by electrostatic deflection, the length of the tube still being reasonably small.

Two pairs of deflecting plates are provided, mounted mutually at right angles. The first pair, nearer the cathode, serves for vertical deflection, and it is to these plates that the voltage to be measured is applied. The second pair of plates, nearer the screen, provides horizontal deflection. A saw-tooth voltage, generated by a special oscillator, is usually applied to these plates in order to obtain the time-base. A photograph of the electrode assembly of a typical oscilloscope tube, together with its symbol, is reproduced in fig. 9–1.

If, between the two plates of a pair, is applied a voltage V_d, the electron beam is deflected by the resulting electric field in the direction of the positive plate. The amount of deflection is given by the following formula:

$$a = \tfrac{1}{2} \cdot \frac{Ls}{V_a d} \cdot V_d, \tag{9.1}$$

where

a = distance of the deflected spot from the centre of the screen,
s = length of plates in the direction of the beam,
L = distance between the centre of the pair of plates and the screen,

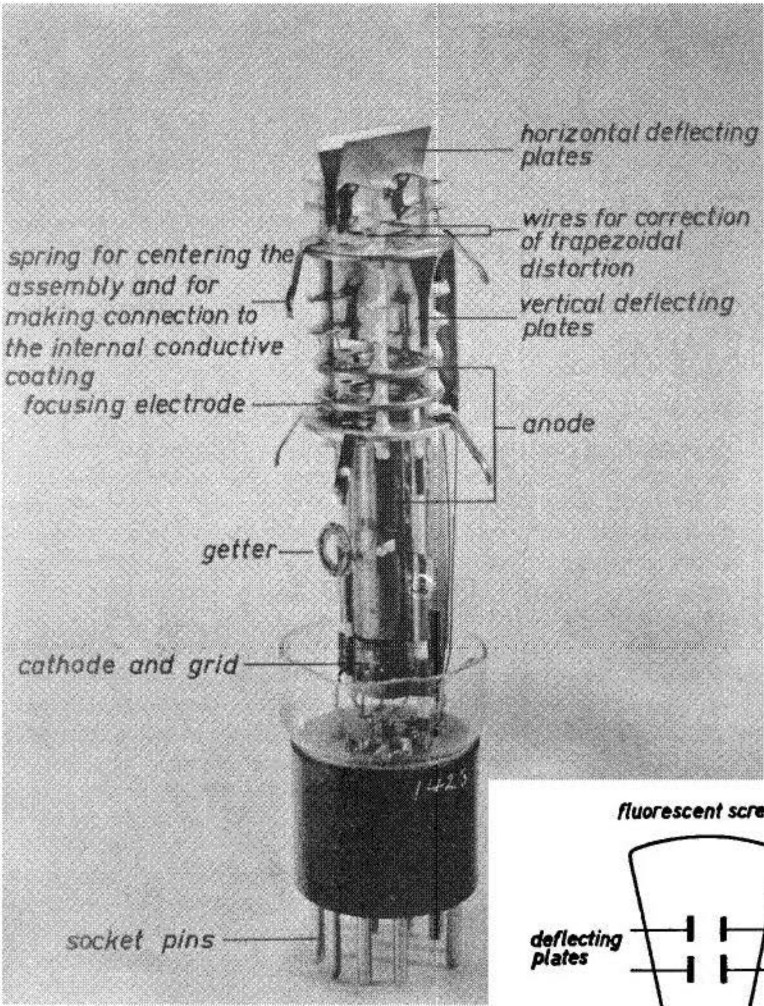
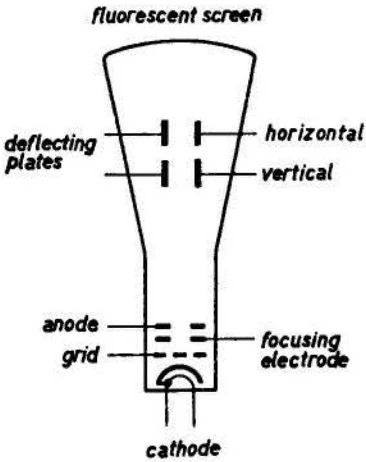


Fig. 9-1. Electrode assembly of a cathode-ray tube.



d = distance between the plates,
V_a = anode voltage,
V_d = voltage between plates.

From this formula it will be seen that the amount of deflection, i.e. the deflection sensitivity, decreases as the anode voltage is increased — in other words the beam becomes "stiff". The conditions for good brightness and for high sensitivity are therefore conflicting. However, tubes of normal construction have adequate deflection sensitivity and brightness for most types of measurement. When very high scanning speeds are required, special tubes are used which incorporate an additional electrode to which a very high potential is applied. This electrode accelerates the electrons after they have left the deflecting plates with a comparatively low velocity.

The simplest way of measuring a voltage is to earth one deflecting plate of each pair, and also the anode, and the positive pole of the high tension unit, and to apply the voltage to be measured and the saw-tooth voltage supplying the time-base to the other two plates respectively. This circuit, however, being asymmetrical with respect to earth, results in certain inaccuracies in the trace unless special precautions are taken. The reason is that the potential at the mid-point between the deflection plates is not constant, but consists of a steady voltage upon which is superimposed an alternating voltage component equal to half the voltage to be measured. The electron velocity is determined by this potential, so that the effective anode voltage is dependent upon the voltage to be measured. Thus, the relation between the voltage to be measured, V_d, and the deflection, a, is not constant and the measurement is not accurate. The inaccuracy is, however, not very serious, and seldom exceeds about 4%.

A somewhat more disturbing consequence of the asymmetrical deflection voltage is trapezoidal distortion. This is due to the fact that the electron beam deflected by the first pair of plates is re-deflected towards the centre of the screen when the potential at the non-earthed plate of the second pair is positive, and towards the periphery of the screen when this plate is negative. This means that the sensitivity of the first pair of plates depends upon the voltage applied to the second pair and this results in trapezoidal distortion.

Both the above faults can be eliminated if the voltages are applied symmetrically to the deflecting plates, but in this case the circuits used for generating the time-base voltage and for amplifying the voltage to be measured are more complex. There are cathode-ray tubes, however, which are specially designed for asymmetric deflection. In these tubes the trapeziodal distortion is compensated by the special shape given to the second pair of plates. The alternating voltage to be measured is applied to the first pair symmetrically, and the time-base voltage is applied to the second pair asymmetrically. In these circumstances the only inaccuracy is that due to the fact that the deflection sensitivity of the second pair depends upon the time-base voltage and results in a slight non-linearity of the time base.

The circuit for asymmetrical operation is so much simpler, however, that where only qualitative examination of electrical magnitudes is required and no accurate measurement is needed, both the voltage to be examined and the time-base voltage are applied asymmetrically. This is quite satisfactory, for example, in cathode-ray oscilloscopes used for the checking and maintenance of industrial electronic equipment.

Cathode-ray tubes for oscilloscopes are made with screens giving green or blue short-persistence traces or with a long-persistence fluorescent screen.

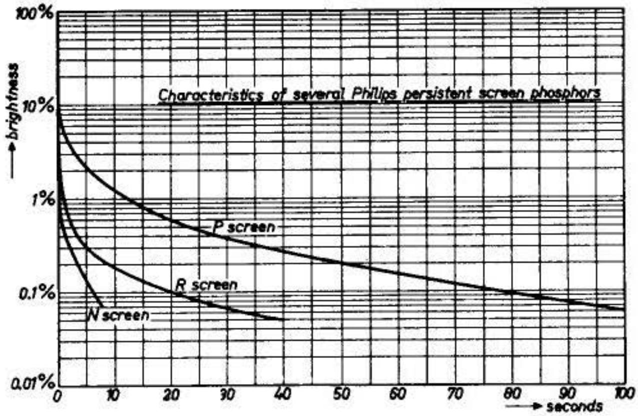


Fig. 9-2. Characteristics of typical persistent screen phosphors.

Generally tubes giving a green trace will be preferred, since this colour is very suitable for direct observation and for photographs taken on negative material. For observing single phenomena or slow-speed processes, a tube with persistent screen should be used, since the trace, once made, remains visible for an appreciable time.

There are several types of screen with different degrees of persistence. Fig. 9–2 shows the performance curves of the Philips type N, R and P screen materials. If pictures are to be recorded directly upon sensitised photographic paper, a blue fluorescent screen is recommended. The spectral responses of green, blue and persistent screens are illustrated in fig. 9–3.

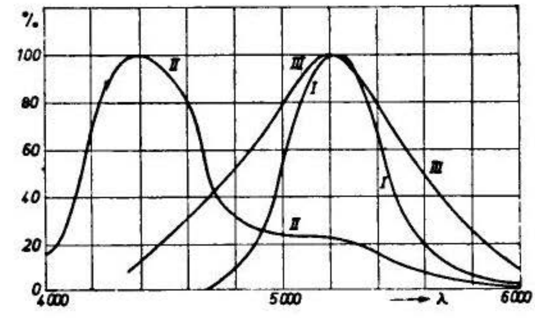


Fig. 9-3. Spectral response characteristics of green (I), blue (II) and persistent screen phosphors (III).

The complete circuit of a simple cathode-ray oscilloscope suitable for industrial applications is given in fig. 9–4. A Philips DG 7–6 cathode-ray tube with a 7 cm diameter screen is used. The equipment includes a pre-amplifier stage for the voltage to be measured, the amplifying tube being e.g. a Type EF 42 high-slope pentode. The amplifier is designed to give almost uniform gain over a frequency range from 4 c/s to 130 kc/s. With such an equipment it is possible to amplify and to record with small distortion even voltages with a form greatly differing from a sine wave; e.g. square-topped waves, saw-tooth voltages etc. The input voltage is applied between terminal O and either terminal E_1 or terminal E_2; the sensitivity at E_1 being 0.14 V_{rms} per centimetre picture height and at E_2, 2.8 V_{rms}.

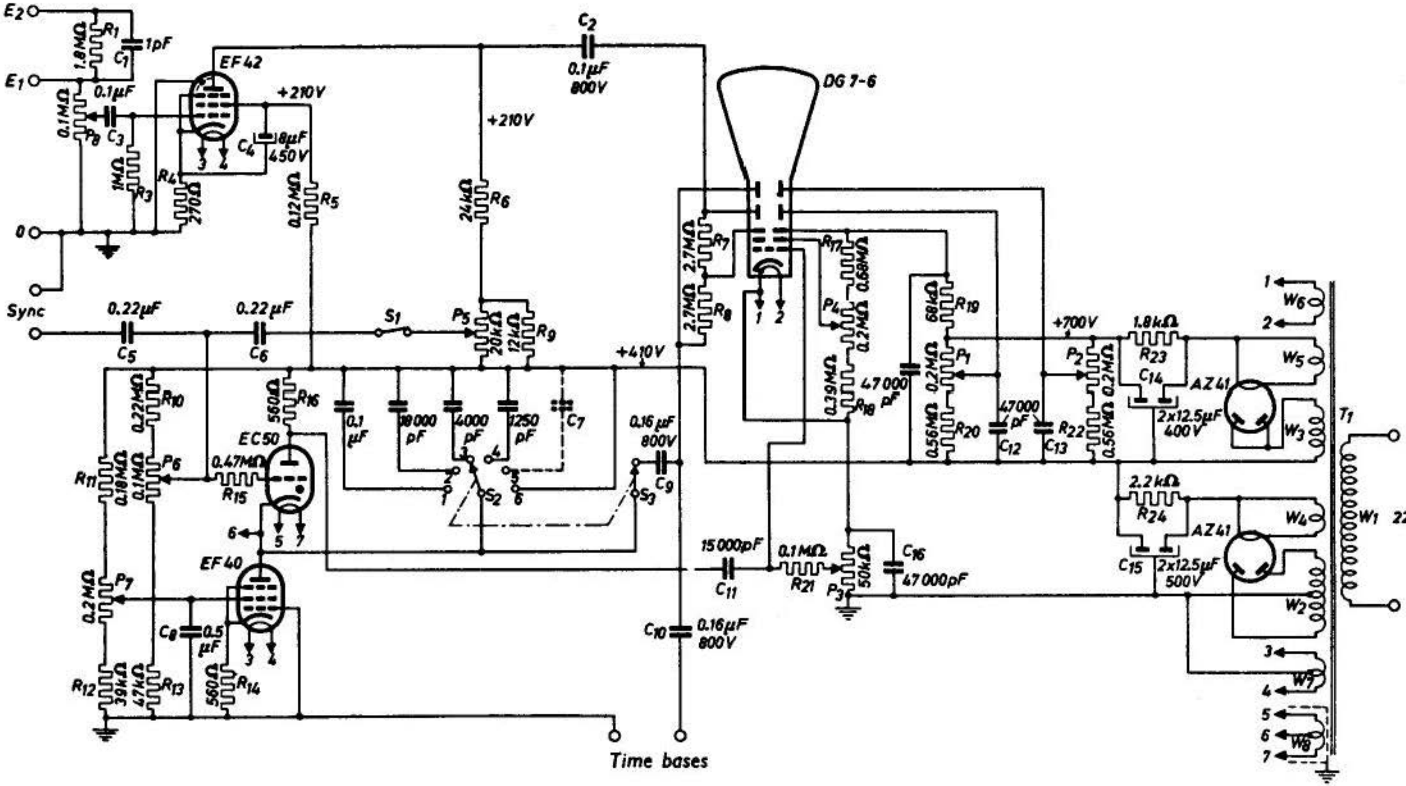


Fig. 9-4. Complete circuit of a simple cathode-ray oscilloscope.

Potentiometer P_8 serves for controlling the output of the amplifier. The amplified voltage is applied to the vertical deflection plates of the cathode-ray tube via capacitors C_2 and C_{12}. A part of this voltage is taken from potentiometer P_5 and is applied to the control grid of the gas-filled triode EC 50 via S_1 and C_6, thus effecting synchronisation of the time-base oscillations. The time-base voltage is generated by an oscillator consisting of the gas-filled triode EC 50 and the pentode EF 40.

To explain the operation of this oscillator it should first be assumed that capacitor C_7 (4000 pF), which is connected to the circuit by switch S_2 (in position 3), is discharged. The cathode of the EC 50 is now at the same potential as the anode, and the control grid is at a negative potential with respect to the cathode via P_6. Capacitor C_7 now charges slowly through the EF 40 tube and the voltage across the capacitor increases linearly. The potential of the cathode meanwhile falls at the same rate, and the grid becomes more positive until finally ignition of the gas-filled triode occurs and C_7 rapidly discharges through the EC 50 and resistor R_{16}. After the discharge the tube again becomes non-conducting, and the cycle repeats. The voltage developed across C_7 during the cycle is of saw-tooth waveform, as depicted in fig. 9–5, and this voltage is applied to the pair of plates for horizontal deflection, via the capacitors C_9 and C_{13}.

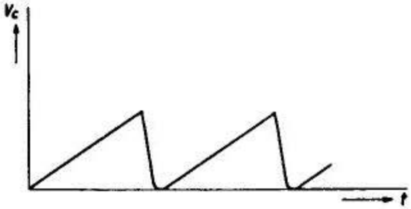


Fig. 9-5. Saw-tooth voltage across capacitor C_7 of fig. 9-4.

The frequency of the saw-tooth voltage can be approximately adjusted by connecting different capacitances C_7 by means of switch S_2. Fine adjustment is obtained by varying the screen-grid voltage of the EF 40 tube by means of potentiometer P_7. The capacitance switched in by position 5 of S_2 consists of the capacitance between the heater winding W_8 on the power transformer and the core, and also the stray capacitance of the circuit.

In position 6, the saw-tooth voltage generator is switched off, and switch S_3 is simultaneously opened, so that an external voltage for the time base can be applied at the terminals marked "time base".

As previously mentioned, synchronisation can be effected by applying a part of the voltage to be measured to the control grid of the EC 50 tube. Synchronisation can also be achieved by an alternating voltage from an external source, applied to the terminals marked "Sync". For this arrangement switch S_1 must be opened.

The amplitude of the saw-tooth voltage, and hence the width of the picture appearing on the luminescent screen, can be varied by adjusting the grid voltage of the gas triode EC 50 by means of potentiometer P_6. The value of the grid voltage determines the voltage between cathode and anode at which ignition occurs. The range of adjustment of the time-base voltage which can be obtained in this way is from 170 to 300 volts, corresponding to variations in picture width between 3.5 and 6 cm.

During the discharge of capacitor C_7 a heavy current surge occurs through the gas triode. The anode resistor R_{16} limits the value of this current, so that it does not exceed the permitted maximum value of 750 mA. At the same instant a voltage peak is developed across R_{16}, its polarity being such that the anode of the gas triode becomes negative with respect to the positive 410 volt supply.

This negative pulse is applied to the grid of the DG 7–6 cathode-ray tube via C_{11}, and suppresses the beam during the flyback. The grid of the cathode-ray tube also receives a permanent negative bias which is taken from the potentiometer P_3. By varying this bias the brightness of the picture may be adjusted. The positive potential applied to the focusing electrode via potentiometer P_4 can also be varied, for adjusting the sharpness of the image.

The power supply is obtained from two rectifiers, equipped with rectifying

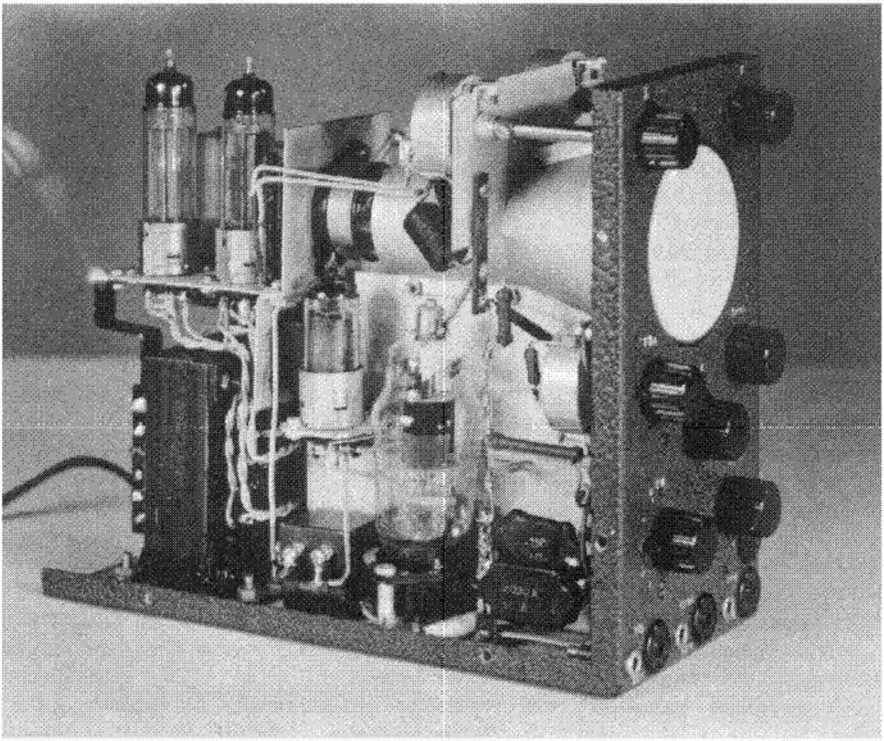


Fig. 9-6. Photograph of the cathode-ray oscilloscope according to fig. 9-4.

tubes AZ 41, one producing 410 volts, the other 300 volts. The 410 volt supply feeds the pre-amplifier stage and the time-base generator, and the two rectifiers connected in series produce a voltage of approximately 700 volts for the anode of the cathode-ray tube. The resistors R_{19}, R_{17}, P_4, R_{18} and P_3 form a voltage divider which supplies the various auxiliary voltages and the anode voltage. Potentiometers P_1 and P_2 serve for vertical and horizontal adjustment of the position of the picture on the screen.

The complete equipment is illustrated in fig. 9–6. Both rectifying tubes, the gas triode and the charging tube are visible, but the pre-amplifier tube is on the other side of the chassis.

When operating a cathode-ray tube care should be taken that the light spot is never allowed to remain stationary or to move only slowly, unless the beam

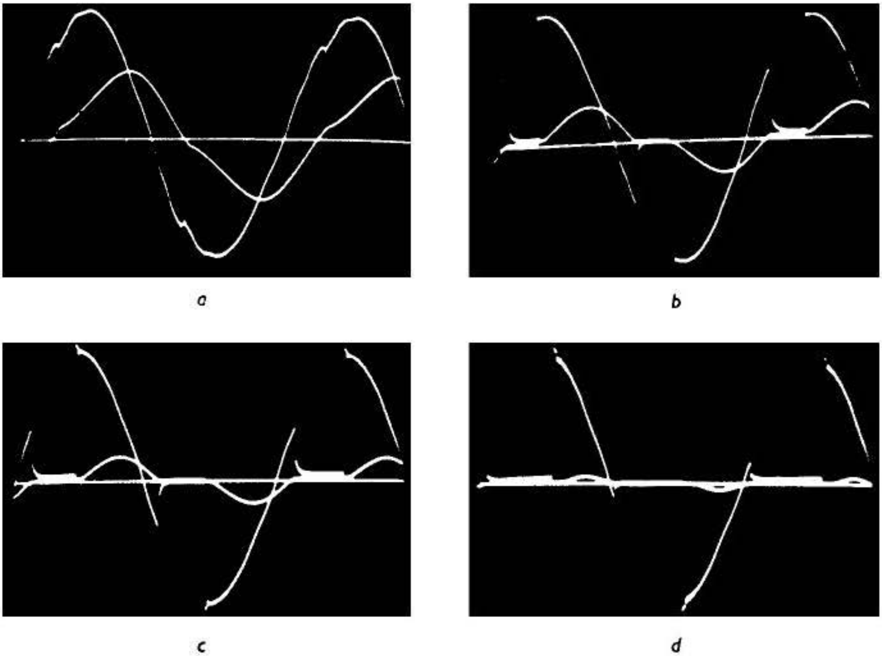


Fig. 9-7. Voltages and currents at an inductive load for two inverse-parallel connected thyratrons as functions of the firing angle (a) 1200 mA, (b) 600 mA, (c) 300 mA, (d) 75 mA (r.m.s. values).

current is first very greatly reduced. Otherwise the screen will be damaged. It is recommended that the time-base generator be kept operating if no voltage is applied to the plates for vertical deflection, so that the spot will not be stationary but will trace a horizontal line.

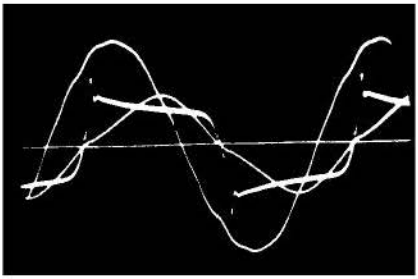


Fig. 9-8. Voltage and current of a fluorescent lamp connected in series with an inductance.

Ambient light falling on the screen reduces the picture contrast. If it is not convenient to shield the screen from stray light, it is recommended to use a filter of a colour similar to that of the light emitted by the screen. Some types of screen fluoresce when ultra-violet light falls upon them. If this occurs a suitable filter should be provided.

To avoid interference by magnetic fields it will generally be necessary to fit the cathode-ray tube with a screen of high-permeability metal, adapted to the shape of the tube. Such a screen can be seen in fig. 9–6.

A good example of the use of the cathode-ray oscilloscope is shown in fig. 9–7. Here, the voltages and currents for two inverse-parallel connected thyratrons operating with an inductive load, are plotted as functions of the firing angle. It may be of interest to compare these photographs with the drawings reproduced in fig. 5-9. Another example is given in fig. 9–8 showing the waveform of current and voltage of a fluorescent lamp connected in series with a choke, which may be compared with fig. 14–5.