Radio Frequency Power Amplifiers

An r.f. power amplifier must deliver a given power at a given frequency into a given load, as efficiently as possible, bearing in mind the type of signal that is to be amplified.

Main Types of Amplifier

1. Continuous Wave. The unmodulated amplifier has to amplify a constant amplitude signal and the signal may be:-

   (a) ON-OFF keyed

   (b) Frequency Shift Telegraphy F.S.T.

   (c) A Frequency Modulated signal.

   This type of amplifier will be operated under Class C or Class B bias conditions.

2. Modulated Amplifiers. An r.f. carrier and an a.f. or video modulating signal are applied separately. Amplitude modulation takes place in the valve. This is known as High Level Modulation. This type of amplifier will also operate under Class C or Class B bias conditions. Most transmitters utilising a double sideband voice output or m.c.w. output, will have this type of power amplifier.

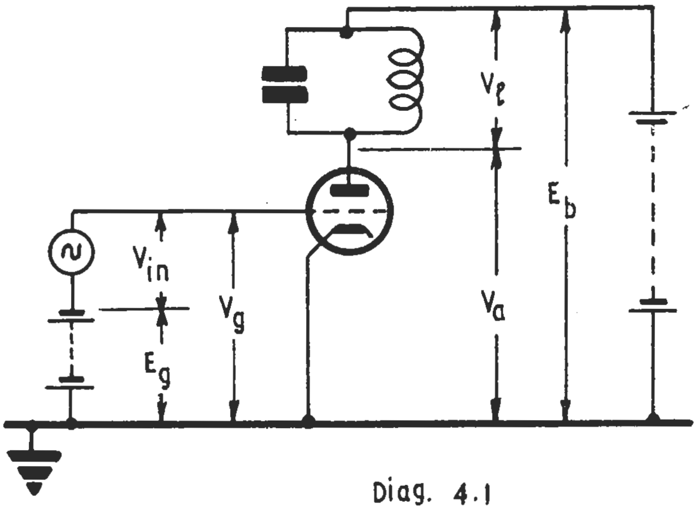
3. Linear Amplifiers. These amplifiers are required to amplify a previously modulated signal without distortion of the modulation envelope.

   If the maximum depth of modulation is 100% then Class B bias must be used. In general Class AB bias is used for linear amplifiers.

   The distributed amplifier is a special case of linear amplifier and will be dealt with later. All transmitters capable of transmitting a single sideband signal will have linear amplifiers.

Class C Amplifiers

The basic amplifier, from which all others may be developed is as shown in Diagram 4.1.



WHERE V_ℓ, V_a & V_{in} ARE VECTOR QUANTITIES

$V_a = E_b + V_\ell$

SIMILARLY

$V_g = E_g + V_{in}$

Diag. 4.1

The anode load is tuned to the operating frequency presenting a resistive impedance to the valve. The r.f. anode voltage is therefore in anti-phase with the r.f. grid voltage.

As the bias, E_g, will be Class C bias, the anode current waveform is non-sinusoidal. It can be represented as a Fourier series containing a d.c., a fundamental and a series of harmonic components.

The selectivity of the anode tuned circuit must be sufficient to select the fundamental component and give a sinusoidal output V_L.

To obtain the highest efficiency, the instantaneous minimum anode potential must be as low as possible. In order to draw the necessary anode current, it is necessary to drive the grid of the valve positive with respect to the cathode and a balance must be struck between the maximum grid potential V_g max. and the minimum anode potential V_a min. To prevent excessive peak grid current and to avoid a reduction of anode current at maximum grid potential V_a min. must exceed V_g max. by a comfortable margin.

The anode-potential swing is determined by the effective anode-circuit resistance and the value of the anode current; the same swing can be obtained by reducing the current and by increasing the resistance.

The power o/p is given by half the product of the peak anode volts and the peak fundamental component of anode current, and if the anode swing is maintained by increasing the grid drive, the power output increases as the anode circuit resistance is decreased.

The peak conditions underwwhich a valve can operate satisfactorily are governed by limits stated by the manufacturer.

The limits set are:-

1. The peak cathode current (some of which flows to the grid)
2. The anode dissipation, which depends on the angle of current flow ϕ and the average anode current.

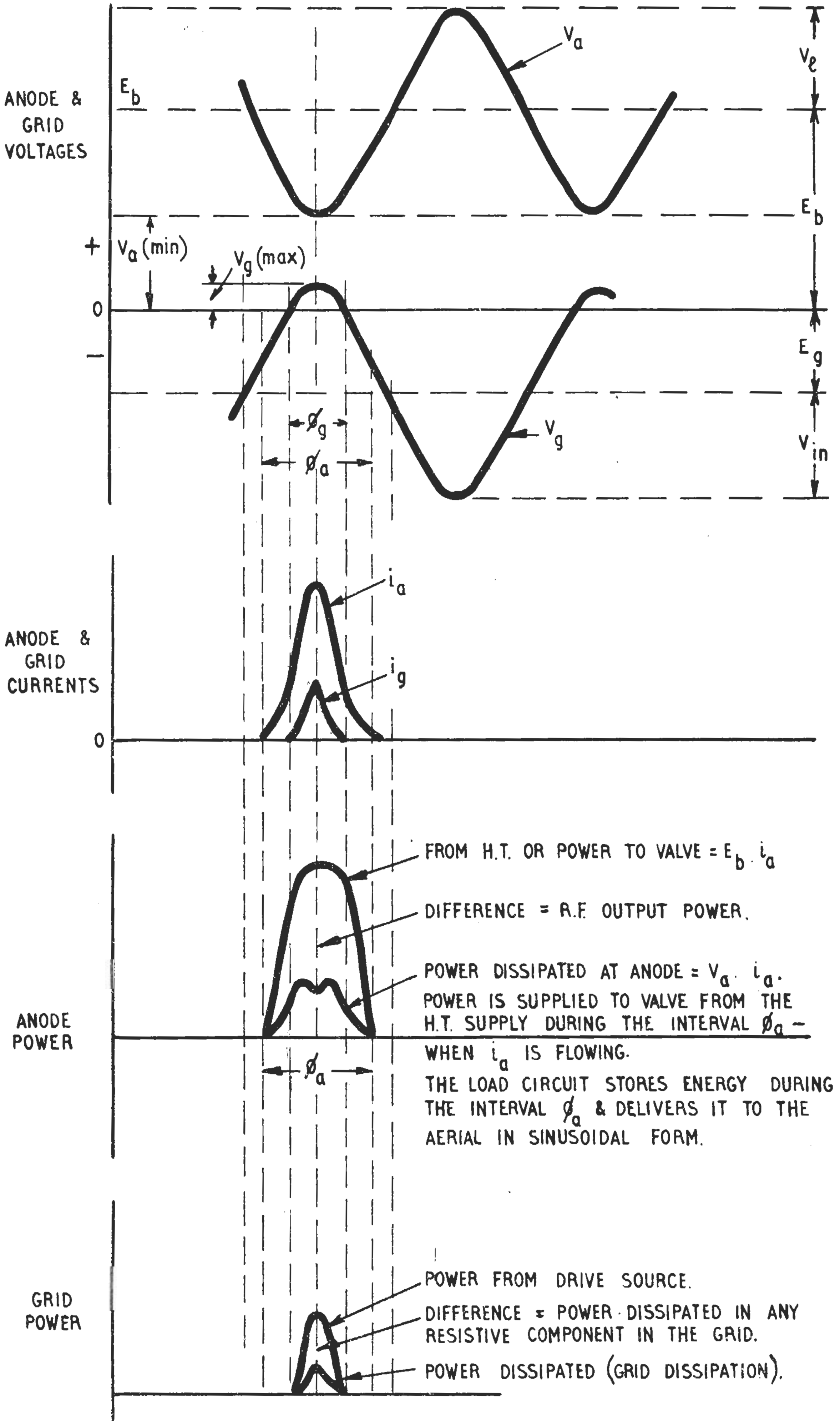
The maximum permissible value of i_a max. is determined by the rated cathode emission. It is this which determines the maximum output power from a given valve and <u>not</u> the rated anode dissipation.

Choice of Angle of Current Flow

The efficiency can be increased by reducing ϕ_a, but this will reduce the output power. Reducing the output power in this manner may necessitate the use of a larger valve to get desired power. The ideal arrangement is to find a valve with ϕ_a about 180°. Since it is unlikely that such a valve is obtainable, the next larger size is chosen and ϕ_a reduced to give sufficient power. This operation will be the most efficient obtainable.

Typical value for ϕ_a is about 170°.

The use of a lower ϕ_a is merely a measure of economy to bridge the gap between available valve sizes.



FROM H.T. OR POWER TO VALVE = $E_b \cdot i_a$

DIFFERENCE = R.F. OUTPUT POWER.

POWER DISSIPATED AT ANODE = $V_a \cdot i_a$.

POWER IS SUPPLIED TO VALVE FROM THE H.T. SUPPLY DURING THE INTERVAL ϕ_a – WHEN i_a IS FLOWING.

THE LOAD CIRCUIT STORES ENERGY DURING THE INTERVAL ϕ_a & DELIVERS IT TO THE AERIAL IN SINUSOIDAL FORM.

POWER FROM DRIVE SOURCE.

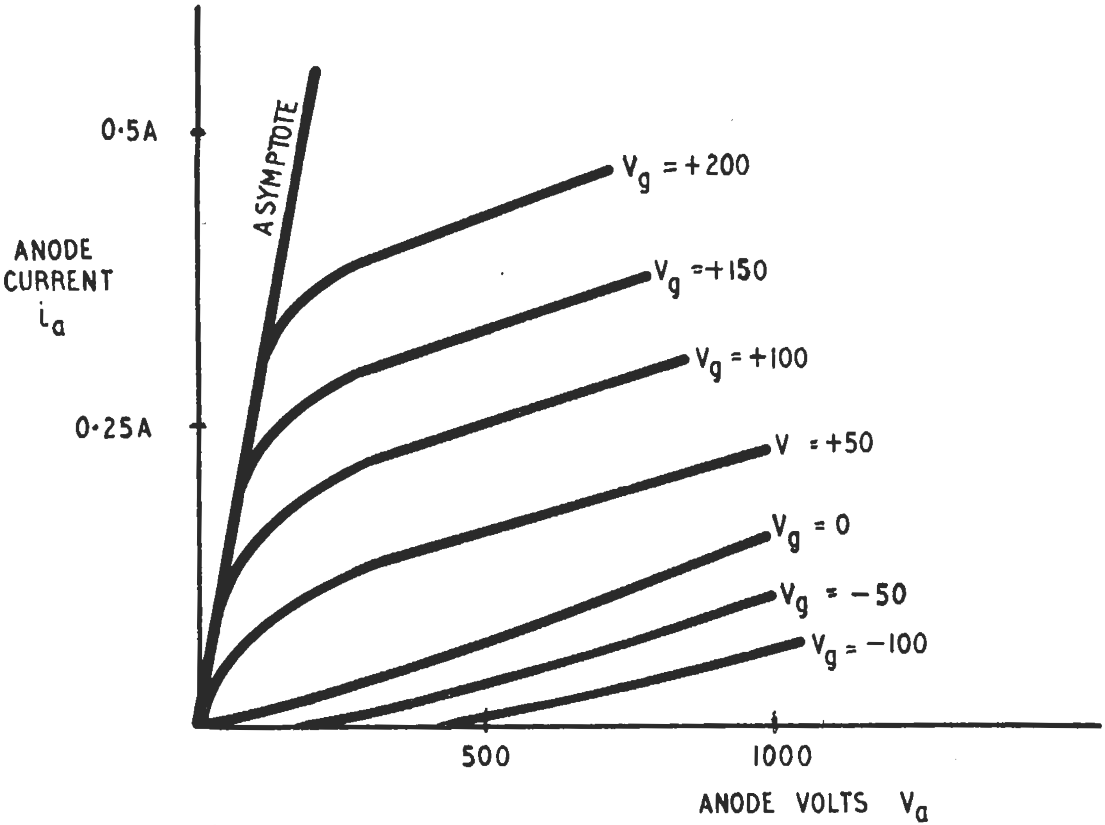
DIFFERENCE = POWER DISSIPATED IN ANY RESISTIVE COMPONENT IN THE GRID.

POWER DISSIPATED (GRID DISSIPATION).

FOR MAXIMUM OUTPUT WE REQUIRE MAXIMUM AREA UNDER THE ANODE POWER CURVE. THUS ϕ_a SHOULD BE AS LARGE AS POSSIBLE (i.e. 180°) TO MAKE i_a AS LARGE AS POSSIBLE.

Anode Modulation of R.F. Amplifiers

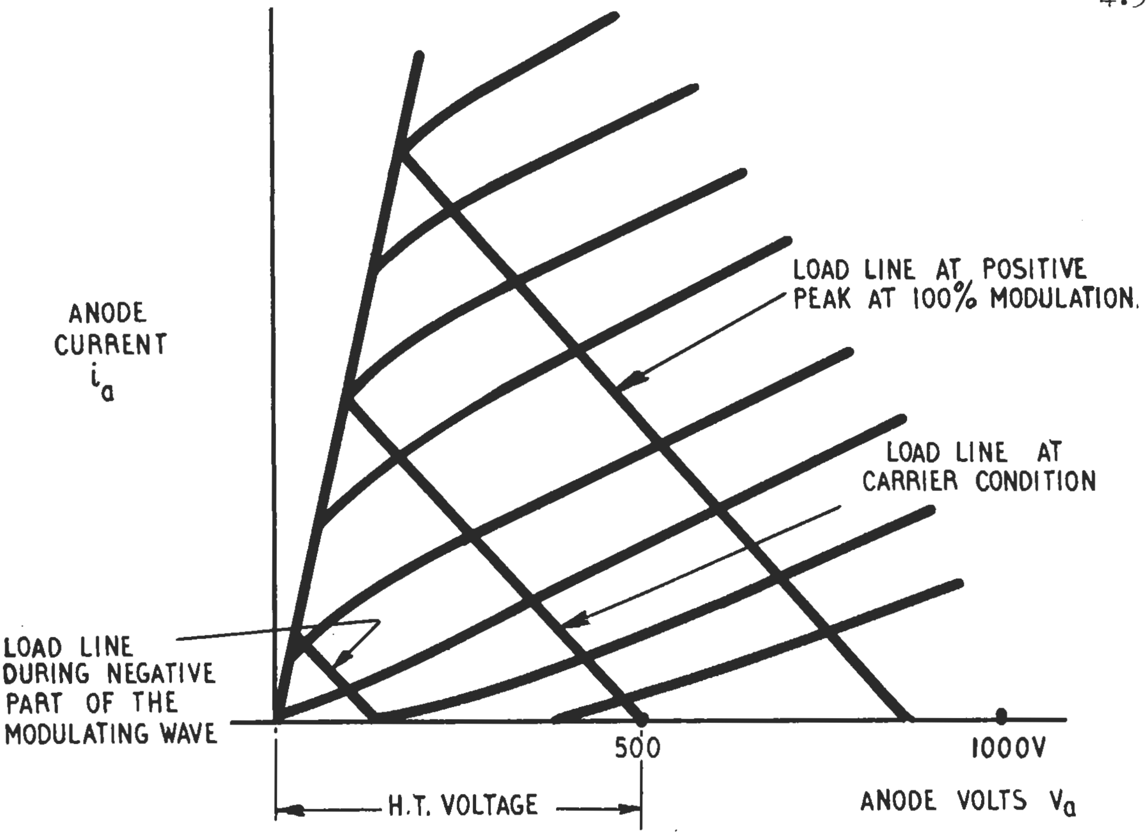
This is the method most commonly used for high power d.s.b. transmitters because it is the most efficient of the simple circuits. It depends for its operation on the fact that the output amplitude obtainable from a valve amplifier is controlled by its anode supply potential. To obtain high efficiency, an increasing necessity as power levels increase, the stage being modulated must be driven "hard".



i_a/V_a CURVES FOR A SMALL POWER TRIODE

Diag. 4:3

The i_a/v_a curves of a triode are shown in Diagram 4.3 and this illustrates that the anode current of a valve ceases to increase with rise of grid potential when the grid and anode potentials are equal. The line corresponding to this condition is known as the "asymptote" because all the anode current/anode potential characteristics are closely asymptotic to it. To a close approximation this asymptote is a straight line. When the grid drive is large enough to meet the asymptote on its positive peaks, the value is said to be driven into "anode limitation". This is the desirable condition for a Class "C" anode modulated stage and to obtain it over the necessary range of anode potential, the grid bias is obtained, at least in part, by "grid leak". The time constant of the grid capacitor and resistor must be less than one-half cycle of the highest modulating frequency. The peak positive grid potential necessary to drive to anode limitation decreases as the anode voltage decreases. The grid current also increases if the grid drive is maintained so that the bias developed across the grid leak increases and the peak positive grid potential is automatically adjusted. Diagram 4.4 shows the valve characteristics with load lines at the limits of anode supply swing as well as the normal carrier condition.



Diag. 4·4

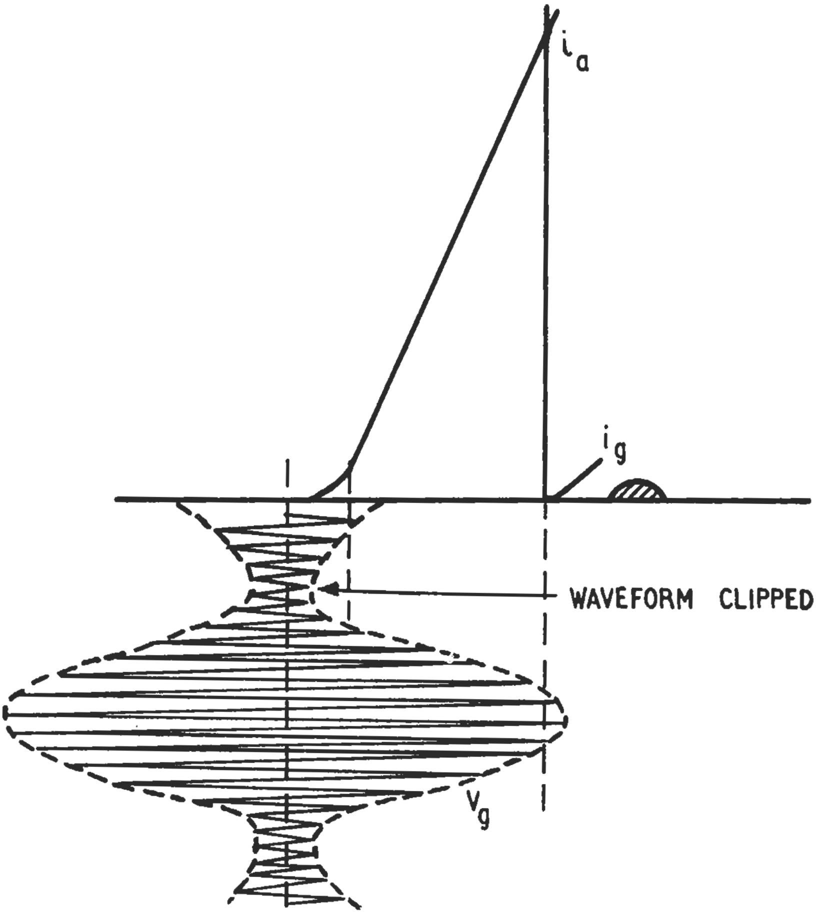
Linear Amplifiers

In modern s.s.b. transmitters, modulation takes place in the synthesiser where the power levels are of the order of milliwatts. This is known as low level modulation. The output of the synthesiser is the radiated frequency modulated as required but at a very low power level. The following Power Amplifiers must therefore amplify the modulated signal to the power required without distorting the envelope. This means that Class "C" can no longer be used and so the efficiency must inevitably be lower.

There are two main causes of envelope distortion in a power amplifier.

1. If Class C bias is employed and the depth of modulation approaches 100%. the negative trough of the envelope will be clipped when the value cuts off. The only way to overcome this is to use Class B bias. All linear amplifiers are biassed Class B and Class AB.

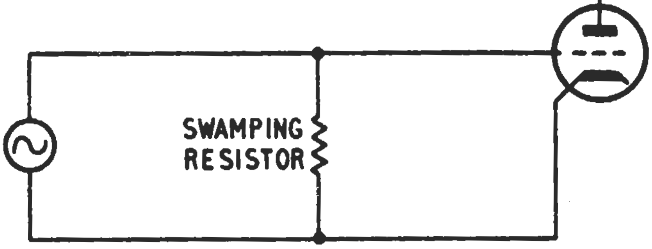
2. Grid current flows on the peaks of the modulation envelope. The drive source will have finite impedance hence the peak of the modulation envelope will be flattened.



Diag 4·5

The obvious way to overcome this is to reduce the drive, so that grid current does not flow at any point on the modulation curve. This reduces the extent to which the value is utilised and so it is only employed on low and medium power transmitters.

The effect of grid current on distortion has been reduced by several means. Early transmitters used grid damping resistors consuming considerably more power than that taken by the grid circuit (Diagram 4.6). This system was obviously wasteful.

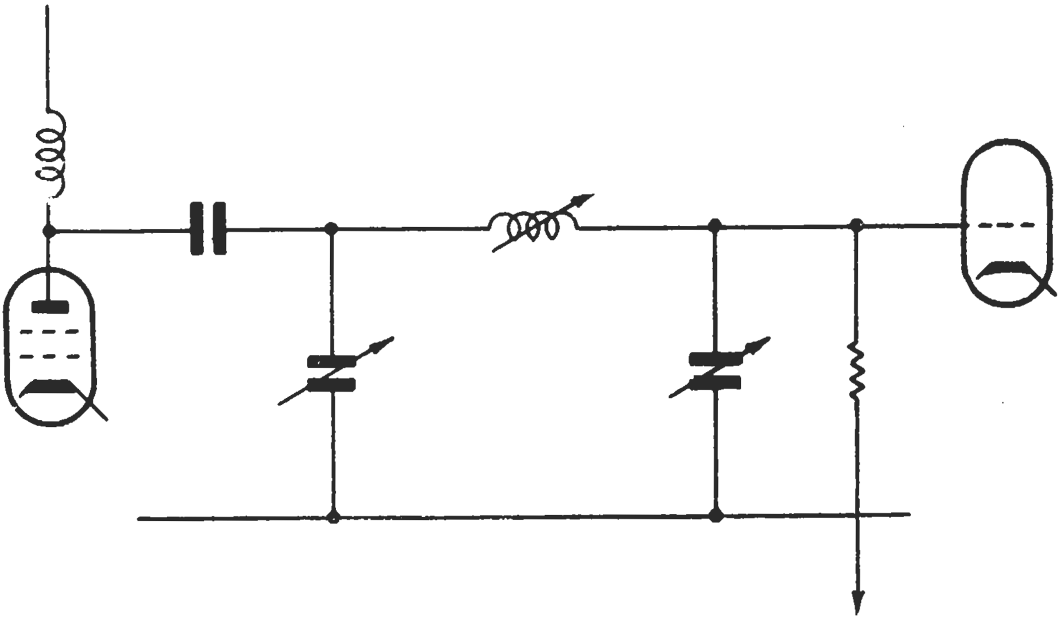


Diag. 4·6

A second method (Diagram 4.7) used was to follow a tetrode valve by a quarterwave network tuned to the radiated frequency. The quarterwave network has characteristics such that a reduction of load at its output terminals results in an increase of impedance at its input terminals. (This network is a π filter and as such

$Z_{IN} = \frac{Z_o^2}{Z_{OUT}}$. If Z_{OUT} should decrease, Z_{IN} will increase).

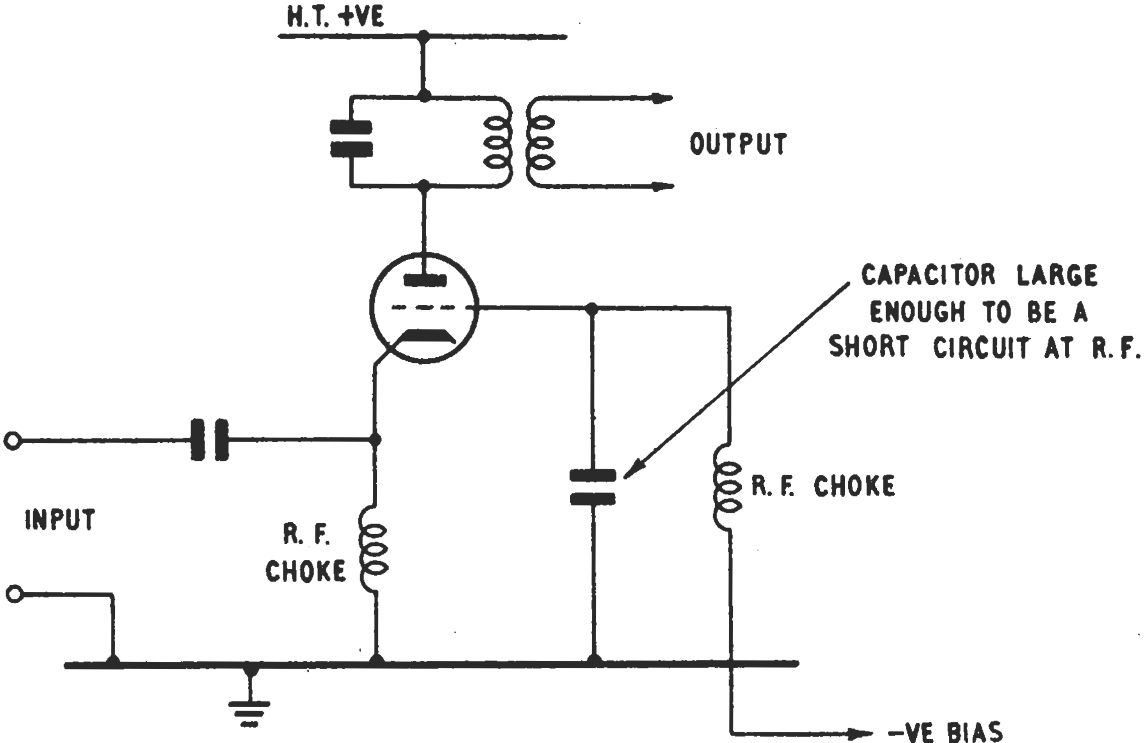
Over the part of the grid excursion where grid current flows, the output impedance decreases, and thus the load as seen by the anode of the previous stage increases. As a tetrode valve is a constant current device, the voltage applied to the π filter increases with increase in input impedance of the network and compensates for changes of grid current, providing very good overall linearity. The major disadvantage of this circuit is that the filter requires three variable elements to be set up for every change of frequency.



Diag. 4·7

Diagram 4.7 <u>$\frac{\lambda}{4}$ Coupling Transformer or π Filter</u>

The third method of reducing this form of non-linearity is by the use of the grounded grid amplifier. This is eminently suitable for linear operation because the grid-cathode load produced by the anode current gives considerable damping on the driving circuit so that the increased damping produced by the grid current is relatively small. The stage driving a grounded grid amplifier has to produce considerably more power output than one driving a grounded cathode stage, but the difference in power, known as "through-put" power, passes to the output circuit of the grounded grid stage and is not wasted. The grounded grid stage does not require neutralisation, a considerable advantage in that the number of circuit elements is reduced making for greater stability of operation.



Grounded Grid Triode

The grid is earthed to r.f. by the capacitor, (d.c. bias is applied to the grid). The input signal is applied to the cathode and the output is taken from the anode in a conventional anode circuit.

Advantages

1. Linear operation.

2. Using a valve specially made for the purpose (i.e. disc seal valves) a simple, compact and well-screened layout is possible.

3. Neutralising is not normally required in the HF band.

4. At VHF and UHF it is easily adapted for coaxial line construction.

Disadvantages

1. When not operated as a linear amplifier, the high power required for the drive may be a disadvantage. The driving power must come from an amplifier stage.

2. If anode modulation is applied, it is usually necessary to modulate both the final stage and the driving stage.

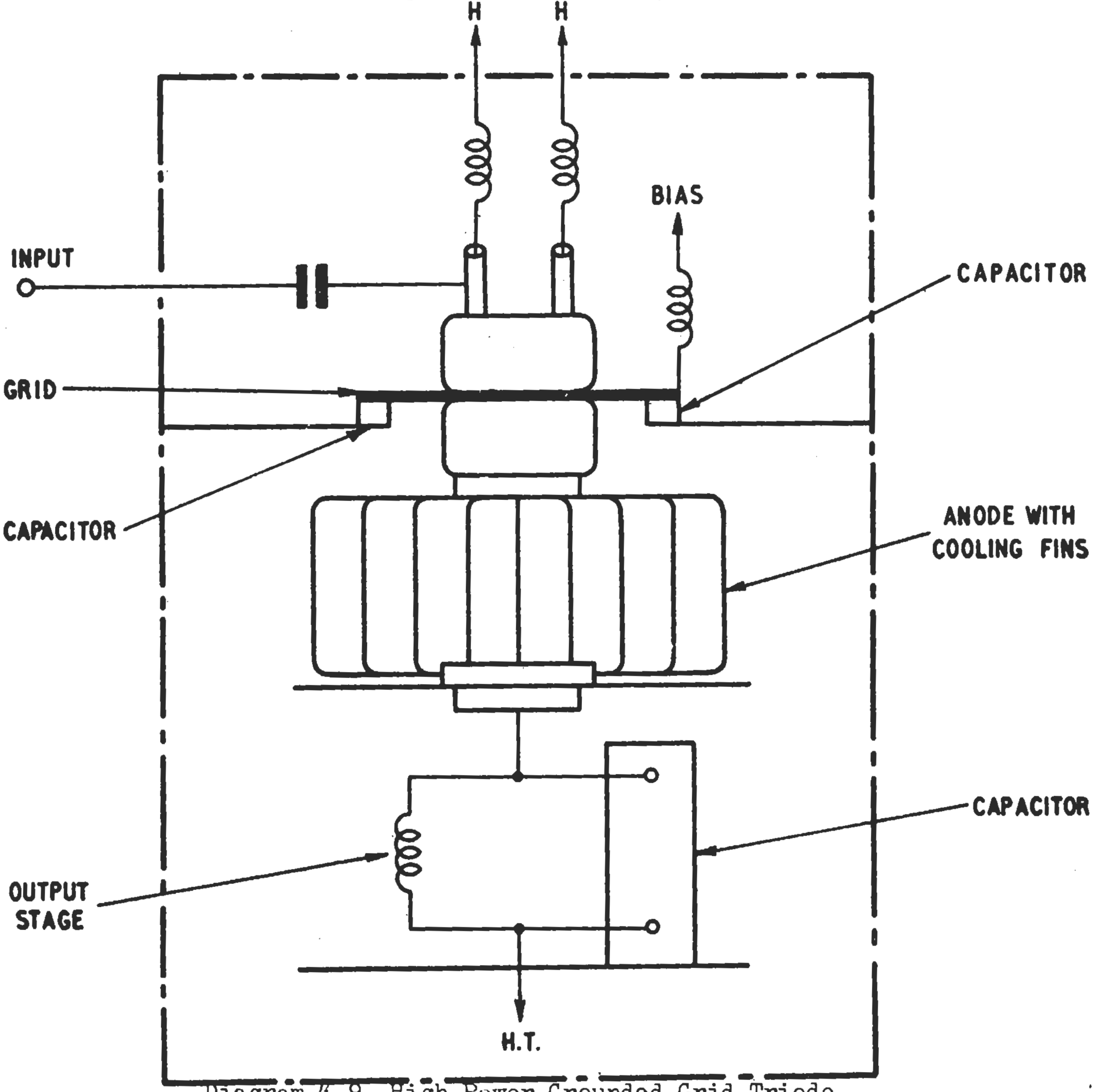


Diagram 4.9 High Power Grounded Grid Triode

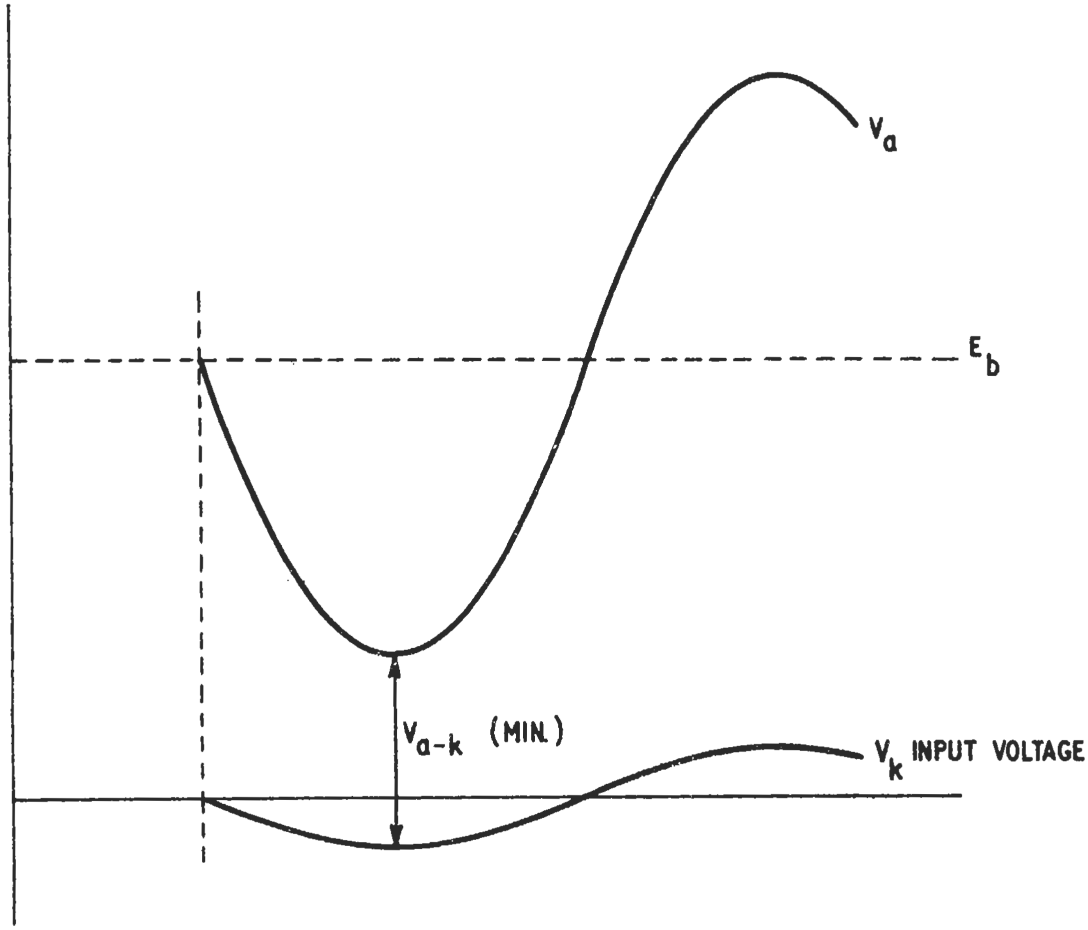
The horizontal screen or grid ring forms a continuous screen between input and output.

The basic design of the valve is no different if the valve is used as a grounded cathode or grounded grid amplifier, but as can be seen in Diagram 4.10 care must be taken with the choice of V_a min.

The cathode voltage is no longer fixed but has a sinusoidal voltage applied to it.

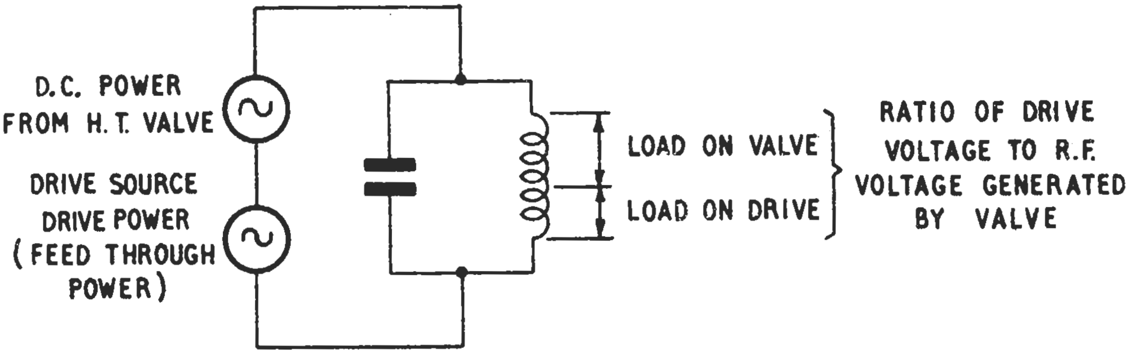
Input and output voltages will be IN PHASE.

It should be noted that the majority of power valves are directly heated.



Diag. 4·10

Gain of a Grounded Grid Triode



Diag. 4·11

$$\text{Power gain } G = \frac{\text{Total Output Power}}{\text{Feed Through Power}}$$

Apparent efficiency $\frac{\text{Total Power Cut}}{\text{D.C. Power from H.T.}}$ may approach or even exceed 100%.

WIDE BAND AMPLIFICATION AT HF

The increased use of the HF bands has focussed attention on problems with which designers, particularly of Transmitters, have been struggling since the early 1920s. The characteristics of the HF band are such that optimum performance requires the operating frequency to be changed at various intervals of time throughout the day and seasons of the year, and these again differ depending on the path length being used.

The designer has to arrange that his equipment can operate efficiently on any frequency within a very wide bandwidth. This covers in fact several octaves, and as network density and interference have increased, this calls for very high standards of performance to be obtained uniformly, despite the very flexible operation imposed.

At first, variable capacitors were more readily available than variable inductors and it was general practice to have interchangeable preset inductors together with a variable capacitor for fine tuning. Electrically, this was very good and worked well, but mechanically such an approach has many limitations and in particular rather a long time was taken to change frequency.

Over the years more sophisticated designs have been introduced but unfortunately it seems difficult to arrange that an attractive and compact mechanical arrangement should be also reasonably efficient electrically. Designs which have a high electrical performance have tended to become, mechanically, too complex. The problems have been aggravated by the demand for remote control and the increasing size of transmitting stations which has involved the use of motorised tuning arrangements.

The problems of motorised control or indeed of tuning comparatively large mechanical structures are in fact, quite severe. This is borne out in practice by the fact that despite the enormous effort and ingenuity which has gone into the solving of problems which have not changed basically for twenty-five years, we are still faced with equipment where electrical faults are out-numbered many times by breakdowns in the mechanical arrangements for changing the frequency of operation.

It is evident that a concept of design that could avoid tuning entirely would have a great deal to commend it, particularly from the viewpoint of the station maintenance engineer.

An equipment that contained no moving parts could be made both mechanically simple and extremely reliable and by implication the changing of frequency could be virtually instantaneous.

A reappraisal of the requirements of a transmitter leads to the idea of a wide band amplifier in which the transmitter will accept signals at a low level within its frequency range and amplify them without distortion of any kind for delivery to an aerial without tuning, switching or adjustment of any kind. For such an amplifier to be successful it must accept widely varying impedances presented to its output terminals.

Wide-band Amplification

This is not a new idea. For many years amplifiers have been built having bandwidths of several hundred Mc/s, but these normally represent only a small portion of the mean frequency of operation. At the lower frequencies, television baseband amplifiers cover bandwidths from very low frequencies up to 5 or even 10 Mc/s, at quite high power levels. To cover the HF band from 2 to 27 Mc/s is not easy and when powers of the order of 1 kW are required sufficient freedom from spurious radiation (which is essential) is not easy to obtain. Such an amplifier will, for the lower frequencies of operation, amplify all harmonics which are generated at any point in the transmitter up to and including the 12th, with no significant attenuation. Exceptional linearity is therefore required since a harmonic content of -40 dB corresponds to a distortion of 1%.

Wide-band amplification up to between 20 and 30 Mc/s as an extension of existing wideband techniques, calls for the use of low impedance valves in which a considerable anode current swing is allied to low capacitance - since the anode load which can be utilised in a normal amplifier is governed by the upper frequency limit and the anode capacitance of the valve.

All modern valves capable of delivering a power of the order of 1 kW are far from perfect in this respect. Parallel operation of small valves gives an improved performance not because parallel connection is in itself advantageous but because the smaller valves currently available are inherently more suitable for wideband amplifiers. A further problem arises in that the power output delivered by a simple amplifier is directly affected by the load impedance into which it is operating. To lay down that the amplifier must work into a load which is mismatched to a degree corresponding to a 2 : 1 S.W.R. severely restricts the already low performance that is obtainable. For certain circumstances the mismatched load can present a resistive impedance to the amplifier either twice - or half the correct value and therefore wide fluctuations of power will be obtained.

It is well known that in a normal cascade amplifier, no matter how complicated the interstage network used the Gain-Bandwidth product can never exceed a certain maximum.

The maximum uniform amplification that can be obtained using one valve is:-

$$A = \frac{g_m}{\Delta f 2\pi C}$$

where g_m = mutual conductance

Δf is the Bandwidth

C is the total anode capacity

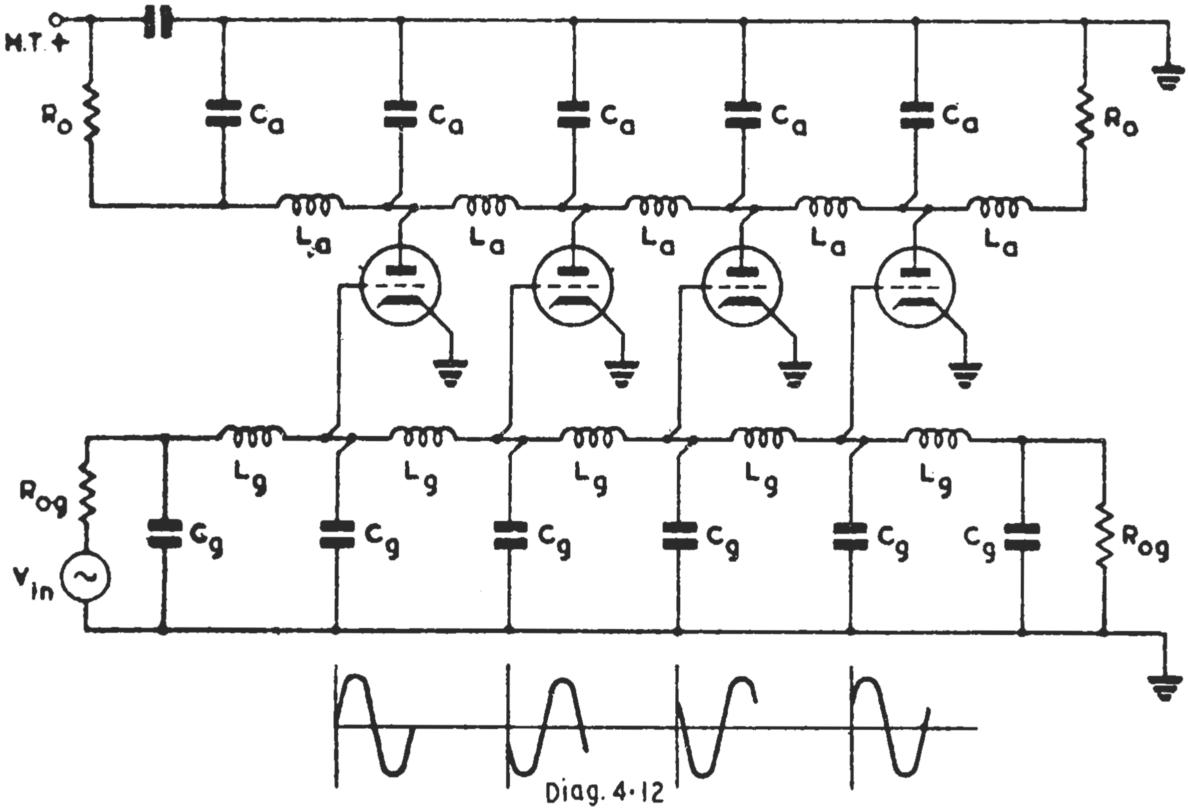
This cannot be bettered by paralleling the valves because as g_m is doubled so is the capacity.

A solution must be sought which brings about a much higher ratio of available current to effective anode capacitance and which is also virtually independent of the load presented to the amplifier.

Distributed Amplifier

In this amplifier the valves are paralleled in a special way, the capacities being separated and the g_m of the valves added without limit. In its simplest form the distributed amplifier uses the valve capacities as part of a transmission line.

Basic Distributed Amplifier



Diag. 4·12

A generator connected to the grid lines will cause a wave to travel along the line. As the wave arrives at the grids of the valves current will flow in the anode circuits, each valve trying to propagate equally in both directions along the anode line. The wave travelling along the anode line to the right will increase according to the number of valves as all the components add in phase. This wave provides the useful output. The wave travelling to the left will be completely absorbed by the dummy load. The power dissipated in this dummy load will depend upon the frequency and at low frequencies almost half the power will be dissipated. In a distributed amplifier the anode and grid lines are designed to have the same velocity of propagation. Overal Gain can be achieved even if the gain per valve is less than unity and is limited only when the transmission line losses per section exceed the gain per valve.

Gain of a Distributed Amplifier

The least number of valves to produce a desired total gain 'G' results when each stage (consisting of 'n' sections) has a gain of 'e' and the stages are cascaded 'm' times.

The number of sections 'n' must be large enough to produce the gain 'e' over the BW required and therefore depends on the valve used.

Let Z_{01} = characteristic Z of the grid line

Z_{02} = characteristic Z of the anode line.

Neglect line attenuation and apply a voltage 'v' to the grid of each valve.

Current flowing in each anode circuit will be g_m'V' mA.
A.C. voltage developed at the anode of each valve

$$= \frac{g_m v\, Z_{02}}{2} \text{ volts.}$$

A.C. voltage developed at the anode of 'n' valves = $\frac{n g_m v Z_{02}}{2}$ volts if each stage consists of 'n' sections, gain per stage

$$A = \frac{n g_m Z_{02}}{2}$$

If 'm' stages of such an amplifier are cascaded

$$A^m = G$$

$$\text{i.e.} \quad N = \frac{2}{g_m Z_{02}} G^{\frac{1}{m}}$$

Now let n.m. = N the total number of valves in amplifier

$$N = m \frac{2}{g_m Z_{02}} G^{\frac{1}{m}}$$

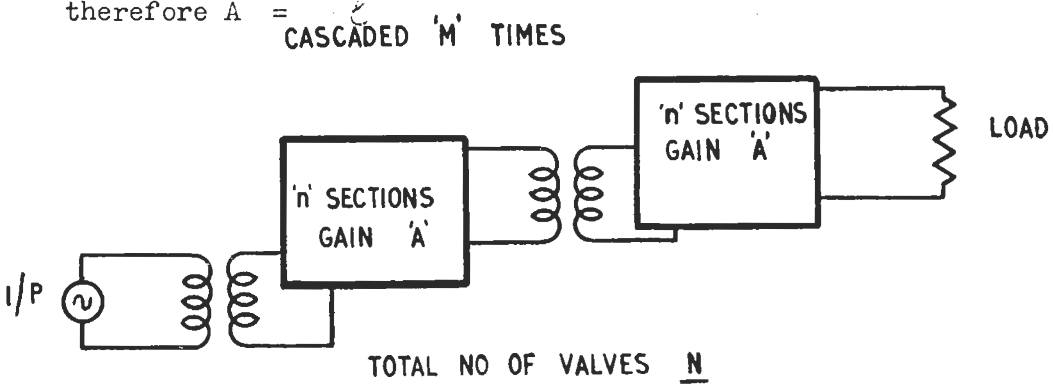
The smallest number of valves will be used when $\frac{dN}{dm} = 0.$

This gives $m = \log_e G$

or $e^m = G$

but $A^M = G$ - proved

therefore A = e



Diag. 4·13

It has been shown that to produce a total gain G the least number of valves is used when the gain of each stage, consisting of 'n' sections has a gain of e. From this it can be shown that the number of stages

$n = \frac{2e}{g_m Z_{02}}$ where Z_{02} is the impedance of the anode line.

Therefore before the number of sections can be determined Z_{02} must be known and this can be calculated knowing the cut off frequency of the amplifier.

$$\text{i.e.} \quad W_{co} = \frac{2}{\sqrt{LaCa}}$$

This gives the value of La and then $Z_{02} = \sqrt{\frac{La}{Ca}}$ can be found.

Z_{01} the characteristic impedance of the grid line can also be calculated knowing the cut off frequency of the grid line.

i.e. $W_{co(g)} = \frac{2}{\sqrt{V_{LgCg}}}$ and then $Z_{01} = \sqrt{\frac{Lg}{Cg}}$

Cut Off Frequencies

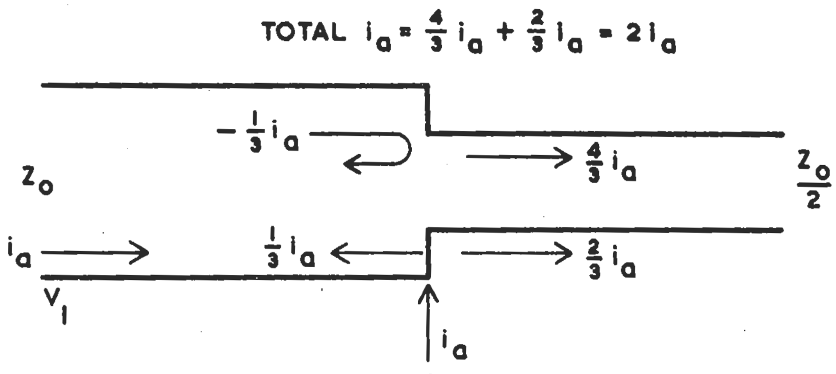
If the cut off frequencies of the grid and anode lines are the same, then instability can occur as the impedances rise to a high value near to cut off. For power considerations, the anode line cut off frequency is kept near to the edge of the band, thus the grid cut off frequency must be increased. A simple method of doing this is to increase the number of grid line filter sections between the valves i.e. two sections of grid line to one section of anode line. To have the same total phase shift as before, the cut off frequency of the grid line will now be about twice as high. The resulting loss of gain is about 3 dB, but stability is ensured.

Tapering the Line

The number of valves and the h.t. employed are adjusted to permit optimum operation at the low frequency end of the band where half the developed power is dissipated in the terminating resistor. In general, as the frequency is increased, only the final valve of the amplifier will be operating at optimum performance due to the presence of standing waves on the line.

By tapering the characteristic impedance of the anode transmission line, the need for an artificial termination at the input end of the amplifier is removed. However, when considering very wideband amplification no improvement in efficiency is obtained due to the poor efficiency at which each valve operates. Where an anode line of uniform impedance is used, only the last valve operates at optimum efficiency. When a tapered line is employed, the voltage on all valves is the same as that at the first (i.e. too low). A compromise has been adopted in which the early stages of the amplifier constitute a uniform transmission line, and when correct operating conditions have been achieved, the characteristic impedance is changed so as to maintain a constant voltage swing on each succeeding valve.

In addition to the advantage obtained in directing the useful power to the output instead of sharing the power at the input and output, tapering the line will reduce the standing waves present on the line at any instant thereby reducing the insulation problems.



Diag.4·14

Each valve will provide a current of i_a into its anode load.

The anode load is the transmission line and at each discontinuity there will be a current antinode for the current in the line and reflection of energy will occur.

The reflection coefficient:-

$$\rho = \frac{Z_L - Z_o}{Z_L + Z_o}$$

and for this case $Z_L = \frac{Z_o}{2}$ and ρ becomes

$$\frac{\frac{Z_o}{2} - Z_o}{\frac{Z_o}{2} + Z_o} = \frac{1}{3}$$

For the current in the line when reflection occurs $\frac{1}{3}\, i_a$ will be reflected back along the line and by Kirchoffs Laws $\frac{4}{3}\, i_a$ will continue into the new section.

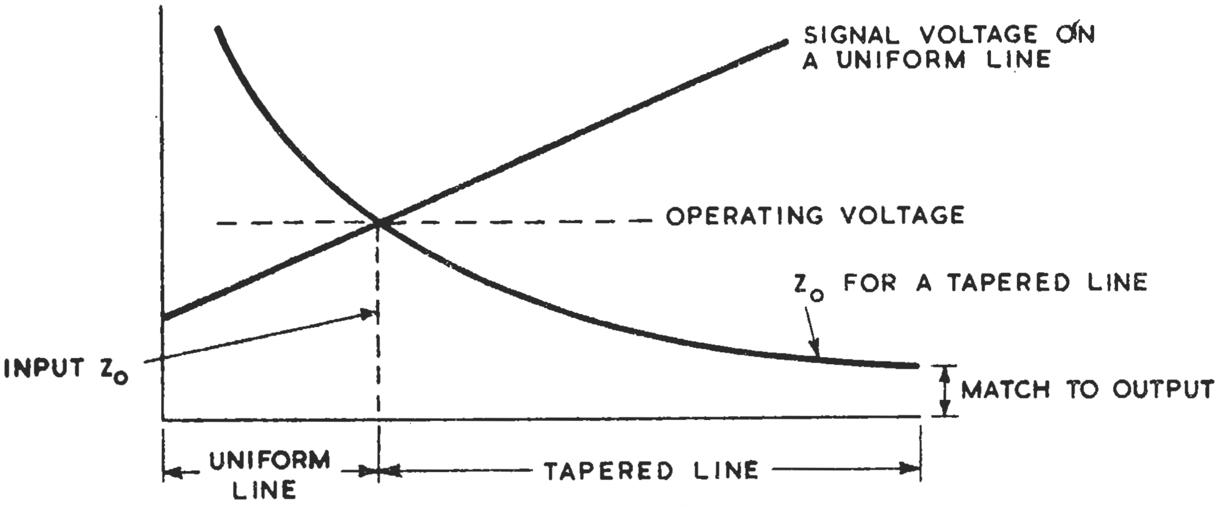
The valve supplying current at the discontinuity is faced with a parallel load and $\frac{2}{3}\, i_a$ will travel along the line and $\frac{1}{3}\, i_a$ will travel back along the line. The two components of $\frac{1}{3}\, i_a$ will cancel each other so that now no current goes back along the line, while the $\frac{4}{3}\, i_a$ and the $\frac{2}{3}\, i_a$ will add making a total current of $2\, i_a$ to be passed along to the next discontinuity and the next valve.

The voltage on the tapered line will be the same all along the line i.e.

$$V = Z_o \times i_a$$

$$V = \frac{Z_o}{2} \times 2\, i_a \text{ etc.}$$

Power must increase as the current increases along the line.



Diag. 4·15

The diagram shows how the voltage on a uniformly tapered line will increase linearly.

If the line is tapered Z_o will vary as shown. The final output impedance will be relatively low (in the 500W amplifier $Z_o = 400\Omega$).

The number of sections of uniform line is determined by the requirement of operating voltage and the input impedance Z_o. The number of sections on the tapered line is governed by the power output required and the final output impedance.

Input and Output Transformers

The design of the input and output transformers is vitally important in a wideband amplifier device, covering say 2 - 28 Mc/s. The output transformer must present an impedance to the line that is constant and match this to the line to the aerial tuning unit, over the operating frequency range.

The double problem of providing a correct transformation ratio at the correct bandwidth for a given power and frequency ranges really determines the limits of the amplifier as a whole.

Ferrite cored transformers are becoming more efficient but to date the problem is still with us.

In some cases two output transformers are used. (One operating from 1.5 to 28 Mc/s and the other from 240 kc/s to 3.5 Mc/s in the 640 Transmitter. These transformers are switched automatically by ledex motor control when the megacycles switch on the synthesiser is set to 3 Mc/s).

The Practical Amplifier

A theoretical solution to the problem of wideband amplification has been outlined and this has been found to be obtainable in practice. The exceptional linearity dictated by International requirements on the levels of spurious radiation, calls for push-pull operation to suppress even harmonics, of which the second is particularly important. Since the second harmonic component of anode current may be quite large in Class AB amplifiers, care is necessary to ensure that the push-push impedance offered to all valves is low at harmonic frequencies. Without considerable care, very high amplitude resonances are possible.

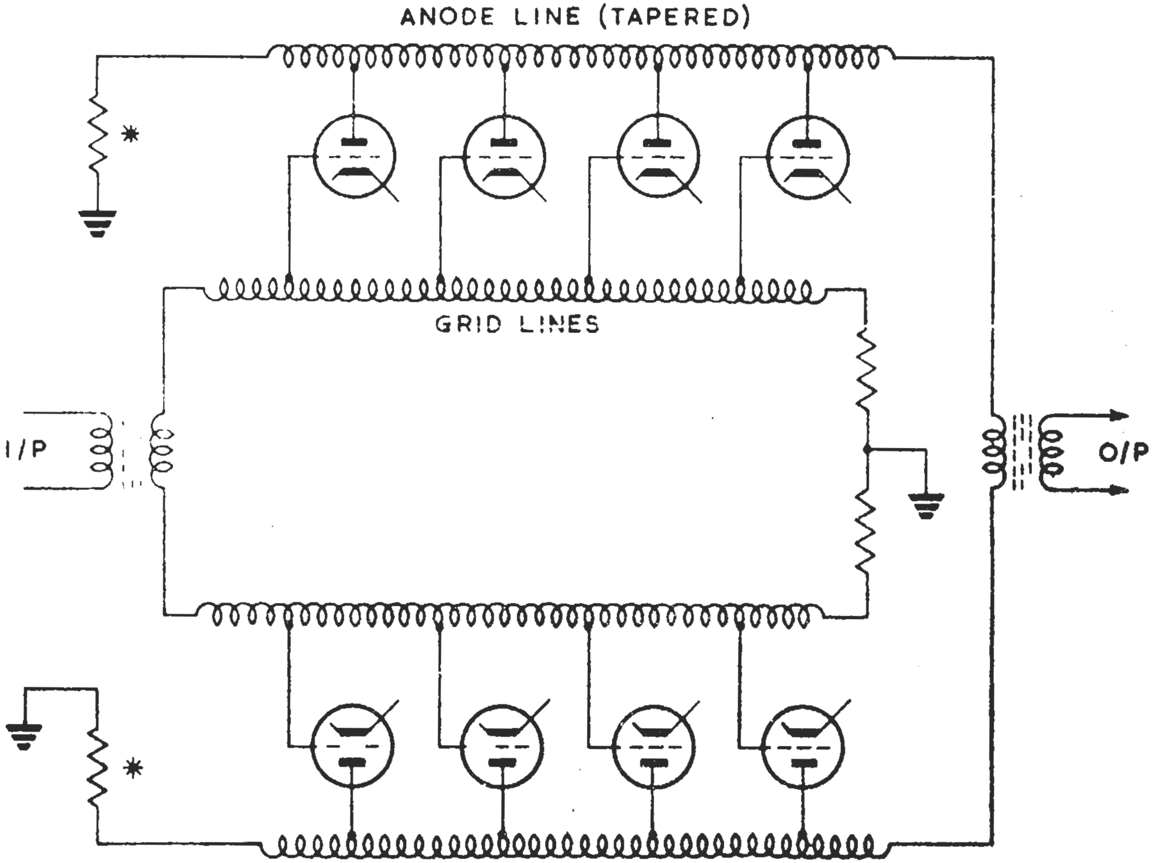
The power output to be obtained from a practical design is, as has been shown, governed by a number of conflicting factors. For widespread application a C.W. power rating of the order of 1 kW is desirable, since transmitters of this type are widely used in the thousands of smaller transmitting stations in which reliability of operation and flexibility in service are of major importance. Increases in power above 1 kW are likely to restrict the advantages of amplifiers of this kind over conventional amplifiers, since the greater simplicity and improved reliability are obtained at the expense of considerable input power, the overall efficiency is only of the order of 20%. Also the cost of providing valves for the transmitter can be quite high.

While this type of equipment will give perfectly satisfactory results with d.s.b. transmissions only a comparatively low carrier power can be radiated in order to keep within the peak limitations already mentioned. This type of amplifier comes fully into its own where s.s.b. or i.s.b. operation is called for.

The amplifier will accept a S.W.R. of 2 : 1 on the output feeder and this produces only slight reduction of power output. The complete loss of output due to feeder breakdown or disconnection has no detrimental effect upon the amplifier for s.s.b. and i.s.b. operation and even in the case of C.W. results in only slight over-dissipation of the order of 20% on certain of the valves and this has no harmful effects provided that the condition is only temporary.

By virtue of its conception, the amplifier is virtually unaffected by failure of valves other than by inter-electrode short-circuits. It is therefore immune from mains voltage surges and can be maintained in service following the failure of even a fairly high proportion of its valves until it is convenient to service the equipment. It is, therefore much less necessary to provide standby transmitters.

The use of amplifiers of this kind places a limitation on the drive equipment which can be used. Normally i.s.b. drives delivering a signal at the radiated frequency are entirely suitable, but telegraph signals are not normally so. The amplifier possesses no selectivity and therefore the radiated signal faithfully corresponds with that applied at the input. Telegraph drives, normally rich in harmonics of the radiated frequency must be improved to meet existing regulations. The wideband amplifier is itself, capable of meeting these regulations if an adequate drive is available but with new regulations coming into force it is probable that low pass filters will have to be associated with the aerials corresponding to the lower frequencies.



* RESISTORS CAPABLE OF ABSORBING THE POWER SHOULD A SERIOUS FAULT DEVELOP

Diag. 4·16

Linearity and Intermodulation Products

In modern transmitters linearity is of prime importance because any non-linearity anywhere in the system results in the production of Intermodulation Products I.Ps. The odd order of I.Ps. will fall within the intelligence bandwidth and will result in cross talk between channels and a loss in power.

It is known that if two frequencies, f_1 and f_2, are simultaneously passing through a non-linear amplifier, then a whole range of other frequencies, which may be expressed as $mf_1 \pm nf$, and $mf_2 \pm nf_1$, (where m and n are whole numbers) will be produced. The I.Ps that cause most trouble are the odd I.Ps and test gear is built to measure the level of the 3rd order I.P. Two tones f_1 and f_2 are produced, f_2 being of a higher frequency than f_1 but both of equal amplitude. These two tones are used to modulate the transmitter. The 3rd order I.P. $(2f_1 - f_2)$ is then extracted from the demodulated signal and its amplitude measured with respect to the amplitude of the modulating tones. Up to a few years ago an I.P. of - 25 to - 28 dB was acceptable, but nowadays, figures of - 36 to - 48 dB are necessary. This figure of I.P. must be maintained or improved upon for all levels of transmitter output from maximum down to zero.

More recently, a piece of apparatus, known as the spectrum analyses has been developed by the Post Office and is now in general use. This equipment will display on a built-in cathode ray oscilloscope any selected frequency spectrum up to 30 kc/s wide. Sweeping speed of the display is controllable and measurements can be made of all intermodulation products of amplitudes down to 60 dB below each of the single test tones.