TECHNICAL PUBLICATION

Considerations on efficiency of the RF power transistors in the different classes of operation

COE82101

Philips
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CONTENTS

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1 SUMMARY

In this report considerations are given concerning the obtainable collector efficiencies in the different classes of operation of R.F. powertransistors. Also the frequency limitations are being considered.

As an exemple it can be mentiond that our 28 V transistors are able to operate in class-E with an efficiency of 85% up to frequencies of 60 to 70 MHz.

2 INTRODUCTION

Some times we receive questions on the possibilities to improve the efficiency of R.F. power amplifiers. Below some considerations will be given for the different classes of operation of nonlinear amplifiers.

3 CLASS-B OPERATION (V_{BE} = 0)

For most of our transmitting transistors we publish the collector efficiency as measured in a class-B common-emitter narrow-band test circuit. Typically this efficiency is 65 to 70%. This can be explained as follows:

- The current efficiency of a class-B amplifier is: $\pi/4 \times 100 = 78.5\%$
- The loss of the output matching network is appr. 5% because it is designed for a loaded Q-factor of 10 whilst the unloaded Q-factor is appr. 200
- The remaining losses are D.C. and R.F. losses in the built-in emitter and collector resistances of the transistor. The former is necessary for a good D.C. SOAR and the latter for a high reverse second breakdown energy giving the device sufficient ruggedness against load mismatch.

However from this situation there are deviations in both directions; e.g. the BLW89 has an efficiency of only 53%. This is caused by the tuning method of the narrow-band test circuit, because the circuit is tuned for maximum power gain. The corresponding load impedance of the transistor is sometimes strongly reactive. Phase angles of 40 to 45 ° can occur which means that the collector efficiency must be multiplied with the cosine of this angle. If a different aligning method was applied, e.g. with a more resistive dummy load, the same transistor would show a higher efficiency at the cost of some power gain.

The other extreme is formed by transistors like the BLW60 and BLY90 having efficiencies of appr. 80%. This happens only at relatively high operating frequencies where the power gain is only 4 to 5 dB. In such cases a substantial amount of the drive power is fed directly to the output circuit via the collectorbase capacitance and the emitter lead inductance. This causes an artificially high collector efficiency. It is therefore better to compare transistors on the basis of oscillator efficiency being defined as:

$$\eta o = \frac{Po - Pi}{V_{ce} \times I_c}$$

In addition to the considerations above there is a slow decrease of efficiency when the operating frequency comes in the neighbourhood of 50% of the f_T of the transistor. This is caused by the increased capacitive current through the transistors collector and emitter resistances.

4 CLASS-C OPERATION

The collector current efficiency can be improved by reduction of the angle of current flow. This is achieved by a negative base-emitter D.C.voltage, e.g. caused by an external base resistor which is effective for D.C.

We do not recommend this method because a bias voltage in excess of 300 mV in combination with the increased drive voltage may cause continues breakdown of the base-emitter diode leading to degradation of this diode, i.e. higher leakage current and reduced h_{fe}.

On the other hand bias voltages below 300 mV are not very effective.

5 CLASS-D OPERATION

An excellent description of this type of operation is given in Ref.1. From this article some conclusions can be drawn:

- Push-pull operation is required with a very tight coupling between the two transistors. This can for instance be achieved by a complementary pair of transistors (NPN - PNP). However pairs showing sufficient equality of D.C. and R.F. properties are not available. As an alternative a matched pair of NPN-transistors can be used provided that a good combining transformer can be constructed which is only possible at frequencies up to appr. 30 MHz.
- The maximum frequency of operation is further restricted by the switching times of the transistors. For output powers above 10 W this is about 0.01 f_T. This means for our modern transistors with U.H.F. diffusions a maximum of 5 to 10 MHz.

6 CLASS-E OPERATION

6.1 General considerations

Design information on this class of operation can be found in Ref.2 through 5. The most important paper in this respect is Ref.4, section III B, pp. 731 to 732, equations 3.20 through 3.29. The basic circuit diagram is reproduced in Fig.1a en b. The reactance of RFC must be high compared with the load resistance. The series tuned circuit in Fig.1b. must have a sufficiently high loaded Q, e.g. greater than 5. After some re-arrangement of the above mentioned equations we find that:

$$R_L = \frac{2V_s^2}{P_o \times \left(1 + \frac{\pi^2}{4}\right)} = 0.5768 \times \frac{V_s^2}{P_o}$$

$$B = \omega_o C = \frac{2}{\pi \times \left(1 + \frac{\pi^2}{4}\right) R_L} = \frac{P_o}{\pi V_s^2}$$

$$X = \omega_o L = \frac{\pi}{8} \times \left(\frac{\pi^2}{2} - 2\right) R_L = \frac{\pi\left(\frac{\pi^2}{2} - 2\right) V_s^2}{4\left(1 + \frac{\pi^2}{4}\right) P_0} = 0.6648 \frac{V_s^2}{P_o}$$

An ideal transistor (having zero saturation resistance) will then show a collector efficiency of 100%.

Further we know from Ref.4 that the collector peak voltage is 3.562 times the supply voltage and that the collector peak current is 2.862 times the collector D.C. current.

6.2 Practical example

To show the possibilities of class-E operation we choose the BLV 25 which is able to produce 175 W of output power at a supply voltage of 28 V up to a frequency of 108 MHz. In a ‘normal’ class-B amplifier this transistor shows an efficiency of 70 to 75%.

The guaranteed collector breakdown voltage of the BLV 25 is 65 V and the typical value 70 V. To prevent loss of efficiency by clipping of the collector voltage waveform we choose a supply voltage of 20 V.

The allowable collector peak current is 35 A. If we choose 30 A the drop of f_T is less than 20% compared with the point of maximum f_T.

Then the collector D.C. current becomes:
$I_c = {}^{30}\!/_{2.862} = 10.5$ A
and the D.C. input power:
$P_{dc} = 20 \times 10.5 = 210$ W.

The saturation resistance is appr. 0.1 Ω and if we consider the collector current as a half sine wave the saturation loss can be approximated by:

$$P_{sat} = \frac{I_{cp}^2 \times R_{sat}}{4} = \frac{30^2 \times 0.1}{4} = 22.5\ W$$

So the transistor output power becomes:

$P_0 = P_{dc} - P_{sat} = 210 - 22.5 = 187.5$ W

As mentioned earlier the loss of the output matching network is 5%, so the output power of the amplifier will then be:

$P_o' = 0.95 \times P_o = 0.95 \times 187.5 = 178$ W

This gives us a collector efficiency of:

$$\eta_c = \frac{P_o'}{P_{dc}} = \frac{178}{210} \times 100\% = 85\%$$

A question that still has to be answered is: up to what frequency can this performance be maintained? The answer can be found by inspection of the formula for B in the previous section. We must keep in mind that C in this formula is the total capacitance from collector to ground, i.e. the sum of the transistors effective collector capacitance and a possible external capacitor. If we reduce the latter to zero and rearrange the formula we will find the maximum frequency of operation:

$$f_{max} = \frac{P_o}{2\pi^2 C_c V_s^2}$$

C_c is the effective collector capacitance which is 344 pF at a collector voltage of 20 V, so:
f_{max} = 66 MHz.

Unfortunately this is not sufficient to cover the F.M. broadcast band up to 108 MHz. However at least some of the advantage of class-E operation can be obtained by using the RFC to tune out the surplus of collector capacitance. In this way a collector efficiency of 80% is probably possible.

7 FINAL CONSIDERATIONS

An interesting question is whether the BLV25 is a good or a bad transistor for class-E operation. Examination of many Philips and competition 28 V transistors shows that it is a good average. f_{max} depends on the ratio P_o/Cc which does not spread so much.

A much greater improvement is obtained by the application of 12 V transistors. The quantity f_{max} rises then to the double value. However for a supply voltage of 12 V there are no transistors available with the output power of the BLV25.

If we would try to make such a device it would be a very impractical one, e.g. the optimum load resistance would be less than 0.5 Ω and the power gain 3 dB less than that of the BLV25, i.e. 7 to 8 dB.

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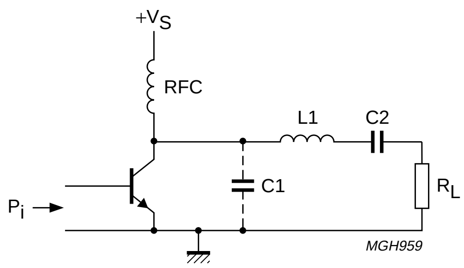

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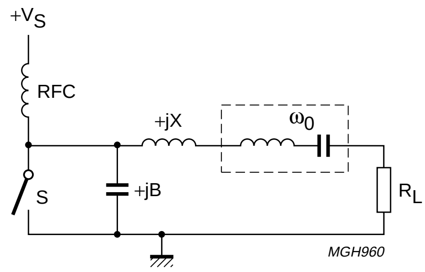

b.

Fig.1

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