UDC 621.314.26 : 621-73

AD 740633

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 71088

April 1971

OUTPUT FILTERS FOR AIRCRAFT TYPE CYCLOCONVERTORS

by

N. J. Carter

SUMMARY

In this Report the performance of low-pass power filters, suitable for cycloconvertors which might be used for the prime electrical power supply in aircraft,is analysed and discussed. Three types of filter are considered and a computer program is used to determine the response of the filters when loads of various power factors are applied. The analysis concludes that the L section filter represents the optimum arrangement for cycloconvertor applications.

Departmental Reference: EP 569

CONTENTS

1 INTRODUCTION

In a variable speed constant frequency (VSCF) system for an aircraft prime electrical power supply, a cycloconvertor may be used directly to convert the variable frequency output (1.2-2.4 kHz) from the engine-driven generator to the required constant frequency (400 Hz). The cycloconvertor fabricates this output from selected portions of the generator supply phases, but the waveform of each phase of output must be filtered to remove the ripple and harmonic components[1]. This Report analyses and discusses filter requirements and performance assuming two types of three phase cycloconvertor, both of 40 kVA rating, and various loading conditions as would be met in aircraft electrical systems. The computer studies involved were concerned solely with filter performance: this was determined using equations defined in the Report and was not influenced by any cycloconvertor interaction. The results are considered, however, against the practical requirements for aircraft VSCF systems.

Four main factors influence the design of a suitable filter:-

(a) Waveform purity. BS 2G100 specifies that total harmonic content has to be kept below 8% of the fundamental rms voltage and no individual harmonic is to exceed 5% of the fundamental rms voltage. The harmonic content before filtering is dependent on the cycloconvertor used and in this Report two types are considered (see section 2).

(b) Weight. This must be kept as low as possible if the VSCF system is to be competitive with constant speed drive systems for aircraft use.

(c) Reactive loads. These can cause a deterioration in the characteristics of the filter, giving insufficient reduction in harmonics. For a particular frequency, the load which will cause the filter to resonate at this frequency is called a critical load. The resonant frequency caused by critical loading is dependent on the filter used, and the value of the load. This is explained in more detail later (see Appendix B).

(d) Voltage regulation. Regulation could be complicated because the voltage transmission factor (i.e. voltage attenuation) of the filter at the fundamental frequency is dependent on the load, which is variable.

Three types of filter were compared using the above criteria, a T section, an L section, and an 'Ott filter'[2]. Whereas the first two are standard designs, the latter was developed specifically for high power static invertors.

The first two types of filter were theoretically analysed, feeding loads up to 14 kVA (single phase) with power factors between 0.5 lagging and 0.8 leading to cover operating conditions met in aircraft. The Ott filter was only analysed as feeding resistive loads for the reasons stated in section 6. The source impedance is dependent on the alternator and cycloconvertor design but is throughout assumed to be zero. This is a simplifying assumption but it is felt that the output impedance is small compared with the impedances of the filter components. Any inductive element in the output impedance of the cycloconvertor can be regarded as part of the filter.

The performance of each filter was theoretically analysed with the aid of a computer; a description of the program is given in Appendix A. Its suitability was assessed using the results of the cycloconvertor performance analysis in Ref.1.

2 CHOICE OF FILTER AND GENERAL DESIGN CONSIDERATIONS

The choice and design of a filter for a VSCF system is dependent on the cycloconvertor power circuit used. In this Report two types of cycloconvertor are considered, a three phase half wave type (Fig.1), chosen for simplicity, and a three phase double Wye with interphase transformers (Fig.2), both of 40 kVA rating. The latter was chosen as it is the only type in commercial production, being used by the General Electric Company. In this system the lower harmonics of the output are controlled by feedback, (referred to by the Firm as wave-shaping feedback).

A survey was made of basic filter designs and Fig.3 shows the three chosen, the T section, L section, and Ott filter. Because of their simplicity, the T section, L section and π section filters were obvious candidates, but the π section was eliminated because the circulating capacitive currents are higher than for the T or L section filters thus increasing radiated interference and the need for screening. The Ott filter was selected as it has a capacitive input impedance, which would eliminate the dc component from the output voltage, and a voltage transmission factor (VTF) that can be arranged to be virtually independent of load at the fundamental frequency of 400 Hz.

Two designs of T section filter (Fig.3a and b) were studied varying only in their cut-off frequency. Thus four individual filters were selected and they will be treated individually.

Filter design depends largely on the cycloconvertor power circuit arrangement and the number of generator phases employed, as implied above.

The main problem in choice and design arises because the load is variable and the filter is usually incorrectly terminated. This causes problems with variation of the VTF in the pass band, due to variation in the gain at the filters natural resonance, and, after cut-off, in the attenuation band due to critical loading.

To explain critical loading, a filter can be represented as an impedance in series with an emf[3]. When the imaginary part of this impedance is cancelled by the imaginary part of the load impedance, resonances can occur and those in the attenuation band can result in insufficient attenuation of the harmonics in the cycloconvertor output. The load reactances which cause these resonances are called the critical loads. Fuller explanation is given in Ref.3. An attempt was made to determine whether normal aircraft loads caused these resonances to occur and if so whether they would be a problem.

Appendix B derives the equations for critical loads for the T and L section filters, and graphs were plotted of the critical load reactances versus frequency using these equations. These results are described in the appropriate sections. In the case of the Ott filter critical loads were not determined as resistive loading only was considered.

The filters will now be discussed more fully.

3 LOW PASS T SECTION FILTER - MARK I

Two filters of this widely-used type were considered differing only in cut-off frequency: they are designated Mark I and Mark II. The circuit and component values of the Mark I filter are shown in Fig.3a and the following design parameters[4] were used:-

(i) Cut-off frequency = the frequency at which the filter enters the attenuation band from the pass band.

(ii) Characteristic impedance = the input impedance of the filter if it contained an infinite number of sections. When terminated with this impedance filter performance is an optimum and the impedance looking in at the filter's input is equal to the characteristic impedance.

(iii) Natural resonant frequency = the frequency at which the VTF reaches a maximum for a filter with its output terminals open circuit.

The values chosen for these parameters were:-

$$\text{Cut-off frequency} = f_C = \frac{1}{\pi\sqrt{LC}} \triangleq 1 \text{ kHz.}$$

$$\text{Characteristic impedance} = z_0 = \sqrt{\frac{L}{C}} \triangleq 1\ \Omega$$

$$\text{Natural resonant frequency} = \frac{1}{2\pi\sqrt{\frac{L}{2}C}} \triangleq 715 \text{ Hz.}$$

The main problem was in choosing the cut-off frequency so that the natural resonance of the filter did not amplify the fundamental frequency and the filter attenuated the harmonics sufficiently. As the fundamental frequency was 400 Hz and the first harmonic was at 1200 Hz this was difficult to do. As will be seen from the results of the computer analysis in section 3.1, wave-shaping feedback, i.e. a feedback loop controlling the thyristor firing angles and thus eliminating the close harmonics, would be needed if this filter were used. The characteristic impedance was chosen so that correct termination was given at maximum loading.

The filter was theoretically analysed feeding unity, lagging and leading power factor loads.

3.1 Theoretical variation of voltage transmission factor and phase shift with load

Analysis showed that above the cut-off frequency this filter has capacitive critical loads (Fig.4) which are unlikely to occur in aircraft as leading power factor loads are not normally specified. Nevertheless, the filter was analysed feeding leading power factor loads to see if resonances occurred or if in fact they were damped out by the resistive component in the load.

Although the effect of several different load power factors were analysed only three will be discussed, these being lagging power factor loads of 0.5, which is the most inductive likely to occur on aircraft, unity power factor loads and leading power factor loads of 0.8. These adequately cover the filter's performance and are discussed next.

3.1.1 Unity power factor loads

Referring to Fig.5 it can be seen that if the filter was terminated with resistances larger than z_0, (i.e. loads <14 kVA) a resonance would occur at 715 Hz giving voltage gain in the filter to frequencies lying in this region. The amount of gain is determined by the magnification factor (Q) of the filter and load combined. This resonance would cause a variation in the VTF at the pass frequency of 400 Hz with load, and would have to be reduced by overall voltage regulation.

In this analysis, the filter attenuated for the first octave after cut-off at a rate of 17 dB per octave for 1 kVA load and 23 dB per octave for maximum load but at high frequencies the rate of attenuation would become the same for all resistive loads at 18 dB per octave.

The variation in phase shift between the output voltage and the input voltage, as derived from the computer program, was quite significant and would cause problems with the feedback loop provided for voltage regulation in a VSCF system. The output voltage lagged the input by $6^{\circ}\ 50'$ for a 1 kVA load, and by $46^{\circ}\ 6'$ for a 14 kVA load. In order to get balanced three phase output, phase correction feedback would be necessary particularly as the load may be unbalanced.

For minimum phase shift at 400 Hz in the filter the frequency to be passed must be as far away from the natural resonant frequency as possible, as shown in the equation (3) below. Assuming a 'loss-less' filter correctly terminated with its characteristic impedance, if β = phase shift in the filter then:-

$$\cos\beta = 1 - \omega^2 \frac{LC}{2} \tag{1}$$

(from Ref.4).

For 90° phase shift:-

$$\omega^2 \frac{LC}{2} = 1 \tag{2}$$

or frequency at which β is 90°

$$= \frac{1}{2\pi}\sqrt{\frac{2}{LC}} \tag{3}$$

$$\hat{=}\ 715\ \text{Hz}$$

which is the natural resonant frequency chosen. In this region the phase shift changes rapidly with frequency, for example with a 1 kVA load, the phase shift at 400 Hz is $6^{\circ}\ 50'$ and at the cut-off frequency of approximately

1 kHz, the phase shift is 180°. The maximum theoretical phase shift that can occur in this type of filter is 270° at infinite frequency.

In this filter the cut-off frequency could not be raised to reduce the above problem, as inadequate attenuation of the harmonics would result unless wave-shaping feedback were employed to remove low frequency harmonics such as the third. This highlights the problem in filter design caused by conflicting requirements.

For resistive loads the filter gave excessive phase shift with heavy loading and had inadequate attenuation to deal with much more than 10% third harmonic. From Fig.5 it appears that any second harmonic (at 800 Hz) would be greatly amplified.

3.1.2 Lagging power factor loads

For lagging power factor loads the resonance below 'cut-off' would be caused by critical loading, which, as can be seen from Fig.4, is inductive between the cut-off and natural resonant frequencies of the filter (i.e. an inductive load, if of high enough Q, would cause a resonance in the pass band of this filter). However as can be seen from Fig.6, loads of 0.5 pF lagging would not greatly affect the cut-off frequency which remained fairly constant, but would cause a slight deterioration in the regulation of the filter at 400 Hz compared with unity power factor loads.

For 1 kVA loads the phase shift was 4° 16' and for 14 kVA loads it was 14° 31'.

On lagging loads the rate of attenuation for the first octave above cut-off was less than for a similar kVA rating on resistive loading, due to a shift in the position of the resonance below cut-off with load reactance. Also less damping of the resonance, was present for a given kVA compared with resistive loads, due to the fact that the filter was delivering less real power to the load. However at high frequencies the rate of attenuation for these loads becomes the same at 18 dB per octave.

Concluding it would appear that on inductive loads the phase shift at the fundamental is less but the attenuation is still insufficient to deal with the lower harmonics without wave-shaping feedback.

3.1.3 Leading power factor loads

With capacitive loads there are two possible regions of voltage gain (see Fig.4), one below the natural resonant frequency, and one above the cut-off frequency of the filter. The problems caused by this latter resonance were stated briefly, in the introduction. The voltage gain at resonance is determined by the combined 'Q' of the filter and load. It was found that no region of voltage gain was present above about 1.2 kHz, for leading power factor loads up to 0.8 power factor. This was due to the damping of the resonance by the resistive part of the load. However, as shown in Fig.7 the distortion in the filter's attenuation characteristics caused by the critical loading could amplify any third harmonic and insufficiently attenuate the others. A graph showing the value of load reactance to cause a resonance at a particular frequency is shown in Fig.4. The resistive part of the load does not alter the position of the resonance but only alters the magnitude. At high frequencies the rate of attenuation with frequency was 24 dB per octave.

The phase shift in the filter at the pass frequency for 0.8 leading power factor loads, again became excessive with heavy loading. At 1 kVA it was 6° 30' whereas at 14 kVA the phase shift was 66° 46'.

Summarising it can be seen that the filter is inadequate for leading power factor loads.

3.2 Variation of current transmission factor (CTF) with load

In standard filter circuits, this parameter is not usually considered but it becomes very important when considering high power filters. Current transmission factor is defined as the ratio current out of filter to current into filter. The larger the input current needed to give the appropriate output current, the heavier the wiring and the larger the thyristors in the cycloconvertor needed to handle it. The alternator would also have to be capable of delivering sufficient current to the cycloconvertor to give the desired output current. For example if the CTF = 0.5 on maximum load the alternator and cycloconvertor would have to be capable of supplying twice the maximum load current. As the voltage transmission factor is fairly constant with load, this would mean that for a 40 kVA system the alternator would have to be able to supply 80 kVA. Thus, it is important to use a filter with a CTF as near unity as possible with heavy loads. Table 1 shows the CTF for different loads on the Mark I filter. The results in the table were calculated by the computor from the program described in Appendix A.

Table 1

Variation of the current transmission factor with load for the Mark I filter

Power factor	kVA	CTF
-0.5 (lagging)	1	0.106
-0.5 (lagging)	14	2.54
1.0	1	0.099
1.0	14	0.988
+0.8 (leading)	1	0.096
+0.8 (leading)	14	0.79

As can be seen from the table the CTF deteriorates as the load decreases: this was confirmed in the laboratory using a 'breadboard' cycloconvertor. The current which flows in the filter but not in the load due to the shunting effect of the filter capacitor is however 'wattless' power, i.e. the input power factor of the filter is almost zero on light loads.

For the maximum load cases the minimum CTF was 0.79 on capacitive load of 14 kVA. For resistive loads it was virtually unity at 14 kVA. For inductive loads the filter's input impedance became virtually resistive at 14 kVA loading. The CTF for a load of 14 kVA, 0.5 pF was higher than would be expected if the VTF was unity:-

Input current to filter × input voltage to filter × power factor of filter plus load

= current out of filter × voltage out of filter × power factor of load

or

$$\text{CTF} \times \text{VTF} = \frac{\text{power factor of filter plus load}}{\text{power factor of load}} .$$

If the VTF = 1 and Load PF = 0.5,

for maximum CTF, power factor of filter plus load, must be unity and therefore

$$\text{CTF} = \frac{1}{0.5} = 2 .$$

However the figure of 2.54 for the CTF with a load of 14 kVA at 0.5 pF

It was considered that for this filter the variation of CTF with load would not cause serious problems.

4 LOW PASS T SECTION FILTER - MARK II

It was observed whilst analysing the Mark I filter, that the VTF remained constant with load at the cut-off frequency and was also equal to unity, in a 'loss-less' filter. This section describes a filter with cut-off frequency equal to the pass frequency of 400 Hz, the aim being to discover if there were any disadvantages which would outweigh its regulation advantage.

With cut-off at 400 Hz it was thought that the natural resonance of the filter would no longer cause variation in the VTF of the filter at 400 Hz, and also that attenuation of the harmonics would be greater.

The filter (Fig.3b) had the following design parameters:-

$$\text{Cut-off frequency} = \frac{1}{\pi\sqrt{LC}} \triangleq 400 \text{ Hz.}$$

$$\text{Characteristic impedance} = z_0 = \sqrt{\frac{L}{C}} = 1\ \Omega.$$

$$\text{Natural resonant frequency} = \frac{1}{2\pi\sqrt{\frac{L}{2}C}} \triangleq 281 \text{ Hz.}$$

The filter was analysed using the same load parameters as in the previous case.

4.1 Theoretical variation of voltage transmission factor and phase shift with load

From Fig.8 it can be seen that the critical loads for this filter were capacitive above cut-off, and inductive or capacitive below cut-off. Thus they affected attenuation of the filter for leading power factor loads only.

The main physical disadvantage of this filter in practice would be its weight, as inductances of 400 μH capable of taking 120 A would be heavy, as would be an 800 μF capacitor capable of dealing with currents of the order of 100 A. The electrical performance is given below.

4.1.1 Unity power factor loads

As can be seen from Fig.9, the natural resonance caused by incorrect termination no longer affects the VTF at 400 Hz, the variation in the VTF at

400 Hz of 1 dB between the 1 kVA and 14 kVA loads, being caused by the voltage drop in the resistances of the filter's inductors. These resistances were calculated by extrapolating the measured dc resistance of the Mark I filter. By winding the inductors with heavier gauge wire this loss could be reduced but at an increased weight penalty.

From Fig.9 it can be seen that the filter attenuates during the first octave after cut-off at a rate of 18 dB per octave for 1 kVA loads, and 24 dB per octave for full load. At high frequencies the rate of attenuation for these loads would become 18 dB per octave as may be confirmed theoretically. The attenuation would be sufficient for both types of cycloconvertor.

Unfortunately it was found that the phase shift in the filter would be very large at 400 Hz due to the positioning of the cut-off frequency. For instance for 1 kVA loads, the output voltage lagged the input voltage by 173° 2' and for 14 kVA loads this increased to 174° 45'. The phase shift was of this magnitude for all loads regardless of power factor and could cause problems with voltage regulation feedback as the response time would be insufficient for fast regulation.

4.1.2 Lagging power factor loads

These loads would modify the position of the natural resonance of the filter due to inductive loads causing resonances below cut-off. However, as shown in Fig.10, this would not affect the VTF at 400 Hz. The difference between the rate of attenuation for resistive and reactive loads was explained in section 3.1.2.

The phase shift was excessive. For 1 kVA loads it was 172° 53' and for 14 kVA loads it was 168° 24'.

4.1.3 Leading power factor loads

These loads (Fig.11) would cause resonances in the attenuation band. On light loads, the resistive component in the load would not sufficiently damp out the resonance due to the capacitive component and a deterioration in the attenuation characteristics of the filter would result. As in the case of the Mark I filter, this filter would not be suitable for feeding leading power factor loads. At high frequencies the rate of attenuation with frequency was 18 dB per octave.

4.2 Theoretical variation of current transmission factor with load

The following table summarises the results obtained from the computer analysis.

Table 2

Variation of current transmission factor with load for the Mark II filter

Power factor	kVA	CTF
-0.5 (lagging)	1	0.036
-0.5 (lagging)	14	0.348
1	1	0.037
1	14	0.442
+0.8 (leading)	1	0.038
+0.8 (leading)	14	0.608

The figures are inferior to those obtained for the Mark I filter as would be expected with the larger filter capacitor. It means that the current rating of the system would have to be more than double the full load current, a serious disadvantage making the whole system bulkier and heavier.

5 LOW PASS L SECTION FILTER

As the rate of attenuation, after cut-off, for an L section filter is less than that for a T section filter due to the latter's extra inductance, it was apparent that the L section filter would be unsuitable for the three phase, half wave type of cycloconvertor unless wave-shaping feedback was employed. It was thus decided to analyse the performance of the L section filter used in the General Electric Company's VSCF system[5]. In this system the lower harmonics are controlled by wave-shaping feedback, so the filter's cut-off frequency is higher and its weight lower. Theory[1] has shown that the first harmonic this filter has to attenuate is the eleventh if wave-shaping feedback is employed.

No practical tests could be carried out on this system due to its non-availability.

For a 40 kVA system, this filter has the following design parameters:-

$$\text{Cut-off frequency} = \frac{1}{\pi\sqrt{2LC}} \triangleq 1680 \text{ Hz.}$$

$$\text{Natural resonant frequency} = \frac{1}{2\pi\sqrt{LC}} \triangleq 1200 \text{ Hz.}$$

(For derivation of formulae see Ref.4.)

This filter was analysed using the same load parameters as for the previous filters.

5.1 Theoretical variation of voltage transmission factor and phase shift with load

This filter is critically loaded by inductance above the natural resonant frequency (Fig.12). Although the inductances to cause resonances in the attenuation region occur in the load, in practice they always have a resistive component. Zero power factor loads are not specified. It was endeavoured to discover if these resistances lowered the overall Q sufficiently to prevent resonance at these frequencies.

5.1.1 Unity power factor loads

As can be seen from Fig.13, the natural resonance of the filter is sufficiently removed from 400 Hz to have little effect on the VTF at this frequency. This is an advantage over the T filter, Mark I, and eases the voltage regulation problem. Attenuation is at the rate of 18 dB per octave for the first octave after cut-off, and this is independent of the load kVA rating. At high frequencies the rate of attenuation becomes 12 dB per octave. This should be adequate in reducing the ripple components in the General Electric system.

The phase shift in this filter at 400 Hz is fairly small, i.e. 45' lag for 1 kVA loads and 10° 12' lag for 14 kVA loads. The low value of phase shift is a by-product of having the cut-off frequency further from the pass frequency than in the case of the other filters described. It is thought that the phase-shift in this filter is not sufficient to cause any problems with voltage regulation feedback. However with unbalanced loading a phase correction network would be needed to maintain the 120° phase shift between the output phases.

5.1.2 Lagging power factor loads

In this case itical loads could cause resonance in the attenuation band, but as is evident from Fig.14, they have no effect on the attenuation characteristics of the filter. This was found to be so for the whole range of inductive loads specified for aircraft. They would become a problem only if the filter were heavily loaded (40 kVA per phase) on virtually zero power factor (<0.1). These conditions are outside the specification. The only resonance which would occur in practice is at the natural resonant frequency of the filter due to incorrect termination.

The rate of attenuation is the same as that for unity power factor loads.

5.1.3 Leading power factor loads

Capacitors would cause critical loading for this filter below the natural resonant frequency. They would produce resonances causing decreased cut-off frequency on heavy loads (Fig.15). This, however, would not appreciably affect the VTF at 400 Hz and, would improve attenuation as compared with lagging and unity power factor loads.

5.2 Theoretical variation of the current transmission factor with load

The table summarises the results obtained.

Table 3

Variation of current transmission factor with load for the L section filter

Power factor	kVA	CTF
-0.5 (lagging)	1	0.11
-0.5 (lagging)	14	1.91
1	1	0.10
1	14	0.82
+0.8 (leading)	1	0.09
+0.8 (leading)	14	0.65

The above figures are better than those obtained for the Mark II T section filter but not quite as good as those obtained for the Mark I T section filter. However although on light loads the CTF is poor, it is not significantly worse than the Mark I filter and is a fault common to all power filters, due to the low characteristic impedance (z_0) required. This causes the capacitor size to be large. In low power filters the capacitor size can be reduced and the inductor values increased.

6 THE OTT^2 FILTER

This filter, Fig.3d, was designed for use with high power invertors. Its four main features are:-

(1) VTF virtually independent of load,

(2) high harmonic attenuation,

(3) series capacitor eliminates the dc component,

(4) a means to commutate the invertor's thyristors due to its input impedance being capacitive. (There is no requirement for this in naturally commutated cycloconvertors.)

The filter component values indicated in the figure, were calculated as follows:- Design impedance, $z_D = \frac{1}{2}\Omega$ as $z_D \ll$ minimum load impedance (1 Ω).

$$\omega_D \hat{=} 2514 \text{ rad/s} = \text{fundamental angular frequency} \quad .$$

$$C_A = \frac{1}{6z_D\omega_D} \hat{=} 133 \ \mu F$$

$$C_B = \frac{1}{3z_D\omega_D} \hat{=} 266 \ \mu F$$

$$L_A = \frac{9z_D}{2\omega_D} \hat{=} 900 \ \mu H$$

$$L_B = \frac{z_D}{\omega_D} \hat{=} 199 \ \mu H \quad .$$

(Formulae obtained from Ref.2.)

It was considered that the size of L_A and the overall weight would be prohibitive for aircraft use, and so the filter was analysed feeding resistive loads only but the results are included as they might be of interest.

As the analysis was not taken any further critical loads were not investigated.

6.1 Variation of voltage transmission factor, phase shift and current transmission factor with load

As can be seen from the graph in Fig.16, resonance would occur at 560 Hz but this would not affect the VTF at 400 Hz, which would remain constant at 3 dB loss. Performance at 400 Hz is summarised in the following table.

Table 4

Load	VTF $= \frac{V_{out}}{V_{in}}$	CTF	Phase shift
80 Ω = 0.165 kVA 1 Ω = 13.2 kVA	0.67 0.61	0.19 1.04	3^o 5' 3^o 28'

Both CTF and VTF at 400 Hz would be lower than that for the other filters considered. The low VTF would be a serious disadvantage as the cycloconvertor voltage would have to be nearly twice the nominal rating for all loads. This would be reflected in increased bulk and weight of the entire generation system. The phase shift in the filter would be low but not enough to outweigh the disadvantages.

7 CONCLUSION

The design of high power filters for use with cycloconvertors is a compromise in both physical construction and electrical performance. It was found that the low pass L section filter would be the best compromise, provided the cycloconvertor was of the double Wye type and employed a wave-shaping feedback circuit to reduce the harmonic content of the output wave. Unlike the T section filters, it would not be affected by critical resonances above the cut-off frequency when on leading power factor loads and only affected in extreme cases with lagging power factor loads. Results of the analysis also indicated that the performance would be satisfactory with unity and lagging power factor loads as regards attenuation and that there would be no serious problem with voltage regulation. Although the current transmission factors were not the best found in the analysis, they were acceptable being unlikely to cause significant penalties in bulk and weight. Use of the leakage inductance of the inter-phase transformers (essential in the double Wye circuit) as filter inductance offers the possibility of useful weight saving. Thus it is evident that the General Electric Company's choice of the L section filter and wave-shaping feedback gives the optimum arrangement in their design.

Despite its higher rate of attenuation, the low-pass T section filter Mark I would also need wave-shaping feedback to remove the lower harmonics and would therefore offer no advantage over the L section filter in this respect. It would be heavier because of the need for an extra inductor, and likely to be inadequate for leading power factor loads - should these occur. For unity power factor loads the variation of phase shift with load would be greater than for the L section filter and could cause problems with voltage regulation on unbalanced loads.

The Mark II version of this filter also exhibited some unsatisfactory performance characteristics. For unity and lagging power factor loads, phase shifts would be even greater than with the Mark I filter, of magnitudes likely to cause unsatisfactory voltage regulation because of poor response in the regulation feedback circuits. With these loads, however, attenuation would be acceptable, but not with leading power factor loads. For all the loading conditions assumed, current transmission factors would be unacceptably low imposing serious bulk and weight penalties.

Although the Ott filter has gained acceptance for use with high power invertor circuits, its application in cycloconvertors is unattractive because of excessive weight. This is due to the series capacitor required to carry full-load current, and to the first series inductor. While the capacitor aids commutation and reduces the dc content in invertors, these auxiliary functions are not relevant in the cycloconvertor.

8 FUTURE WORK

It is intended to verify the results of the analysis of the L section filter in a forthcoming evaluation at RAE of a 60 kVA VSCF system designed and manufactured by the General Electric Company.

During future investigations of alternative forms of cycloconvertor at RAE, further information on filter performance will be gained. Although this should prove useful in expanding knowledge, it would be more satisfactory if an extensive study could be arranged of filters for high power ac circuits. There has been a tendency to neglect this field.

Appendix A

A BRIEF DESCRIPTION OF THE COMPUTER PROGRAM USED TO DETERMINE THE FREQUENCY RESPONSE OF A FILTER

A simplified flow chart of this program is shown in Fig.17. For a particular load power rating and power factor the program calculates the corresponding load impedance and adds it to the output of the filter. It then determines the frequency response of the loaded filter for a range of frequencies from 10-10000 Hz, generated by an internal program drop. The program was easily modified, when required, to determine the frequency response for load power ratings of less than 1 kVA (or greater than 14).

Below is a brief description of the input data needed for the program and the output format.

Input data

(1) Filter component values.

(2) Output voltage required from the filter to be applied across the load - V_{out}.

(3) Power factor of the load - pF.

(4) Frequency of the output voltage, (in all cases 400 Hz).

Output data

For each case the program points out:-

(1) $\left|\dfrac{\text{Output voltage from filter}}{\text{Input voltage to filter}}\right|$ = VTF, as a ratio and also in decibels.

(2) $\left|\dfrac{\text{Output current from filter into load}}{\text{Input current to filter}}\right|$ = CTF as a ratio.

(3) The real and imaginary terms of the VTF to enable the phase shift in the filter to be determined with the aid of (4).

(4) Tan ϕ where ϕ = phase shift caused by the filter. For a phase shift of more than 90^{o} (3) above gives the quadrant in which the output voltage lies with reference to the input voltage, so that the phase shaft can be determined for all cases.

The computer also prints out the calculated load values depending on power factor and kVA rating:-

R_L = load resistance,

C_L = load capacitance, for leading power factor loads,

L_L = load inductance, for lagging power factor loads,

Z_L = load impedance.

Appendix B

DERIVATION OF CRITICAL LOAD EQUATIONS

Here the equations for determining the critical load reactance for a given frequency, for a T section filter, and an L section filter are derived. For simplification the filters are assumed to have no resistive components.

B.1 L section filter

Referring to Fig.18 it can be seen that the impedance of the filter looking in at Q, the output, with the input short circuited is given by:-

$$Z_{SCQP} = \frac{-\frac{j}{\omega C} \times j\omega \frac{L}{2}}{j\omega \frac{L}{2} - \frac{j}{\omega C}} \, \Omega \qquad \text{(B-1)}$$

where Z_{SCQP}, Thevinim's impedance,

$$= \frac{-j\omega L}{\omega^2 LC - 2} \, \Omega \quad . \qquad \text{(B-2)}$$

For the filter to be critically loaded, i.e. voltage resonance to occur, the load's reactance must cancell this impedance.

Therefore

$$\text{load reactance} = \frac{+j\omega L}{\omega^2 LC - 2} \, \Omega \quad . \qquad \text{(B-3)}$$

If the value of equation (B-3) is positive, the load is inductive, and if negative, the load is capacitive.

$\frac{\omega L}{\omega^2 LC - 2}$ is positive when

$$\omega > \sqrt{\frac{2}{LC}} \qquad \text{(B-4)}$$

where $\omega = 2\pi f$.

Now $\omega = \sqrt{\frac{2}{LC}}$ is the natural resonant angular frequency for this type of filter. So for frequencies greater than this, inductive loads can cause resonance, and for frequencies less than the natural resonant frequency of the filter, capacitive loads can cause resonance.

The equation for the critical loads of an L section filter (B-3), is plotted in Fig.12.

B.2 T section filter

Referring to Fig.19 it can be seen that the impedance of the filter looking in at Q, the output, with the input short circuited is given by:-

$$Z_{SCQP} = j\omega \frac{L}{2} - \frac{j\omega L}{(\omega^2 LC - 2)} \;\Omega \qquad \text{(B-5)}$$

$$= j\omega L \left(\frac{1}{2} - \frac{1}{(\omega^2 LC - 2)}\right) \Omega \; . \qquad \text{(B-6)}$$

For the filter to be critically loaded, the load's reactance must cancel this impedance.

Therefore

$$\text{load reactance} = -j\omega L \left(\frac{1}{2} - \frac{1}{(\omega^2 LC - 2)}\right) \Omega \; . \qquad \text{(B-7)}$$

When this term is positive the load is inductive and when negative the load is capacitive.

For (B-7) to be positive then

$$\left(\frac{1}{2} - \frac{1}{(\omega^2 \, LC - 2)}\right)$$

must be negative.

By inspection it can be seen that this is so if

$$2 < \omega^2 LC < 4 \; ,$$

i.e. limits are

$$\omega^2 LC > 2 \qquad \text{(B-8)}$$

$$\omega > \sqrt{\frac{1}{\frac{L}{2}C}} \tag{B-9}$$

and

$$\omega^2 LC < 4 \tag{B-10}$$

$$\omega < \frac{2}{\sqrt{LC}} \quad . \tag{B-11}$$

<u>NOTE</u> $\omega = \sqrt{\frac{1}{\frac{L}{2}C}}$ is the natural resonant angular frequency of the filter

and $\omega = \frac{2}{\sqrt{LC}}$ is the cut-off angular frequency of the filter.

For (B-7) to be negative then:-

$$\left(\tfrac{1}{2} - \frac{1}{(\omega^2 LC - 2)}\right)$$

must be positive.

For this to happen, either

$$\frac{1}{\omega^2 LC - 2}$$

is negative in which case

$$\omega < \sqrt{\frac{1}{\frac{L}{2}C}} \tag{B-12}$$

or

$$\tfrac{1}{2} > \frac{1}{(\omega^2 LC - 2)} \tag{B-13}$$

therefore

$$\omega > \frac{2}{\sqrt{LC}} \quad . \tag{B-14}$$

Therefore the load reactances to cause resonance in this filter are:-

Capacitive for frequencies up to the natural resonant frequency.

Inductive for frequencies between the natural resonant frequency and the cut-off frequency.

Capacitive for frequencies above the cut-off frequency.

The equation (B-7) for the critical loads for the Mark I and Mark II T section filters is plotted in Figs.4 and 8 respectively.

REFERENCES

No.	Author(s)	Title, etc
1	G. W. Wilcock	Analysis and reduction of harmonics and filter weight in aircraft type cycloconvertors. RAE Technical Report 70250 (1970)
2	R. Ott	A filter for SCR commutation and harmonic attenuation in high power invertors. IEEE Transactions, pp 259-262 (1963)
3	W. R. Hinton C. A. Meadows L. C. Caddy	A theory for the design and analysis of radio interference suppressors. RAE Technical Report 66391 (1966)
4	The Royal Signals	Handbook of Line Communication. Vol.1 HMSO, Chapter 15
5	General Electric Company	VSCF review and work session. WEC 1004 (1968)

Fig.

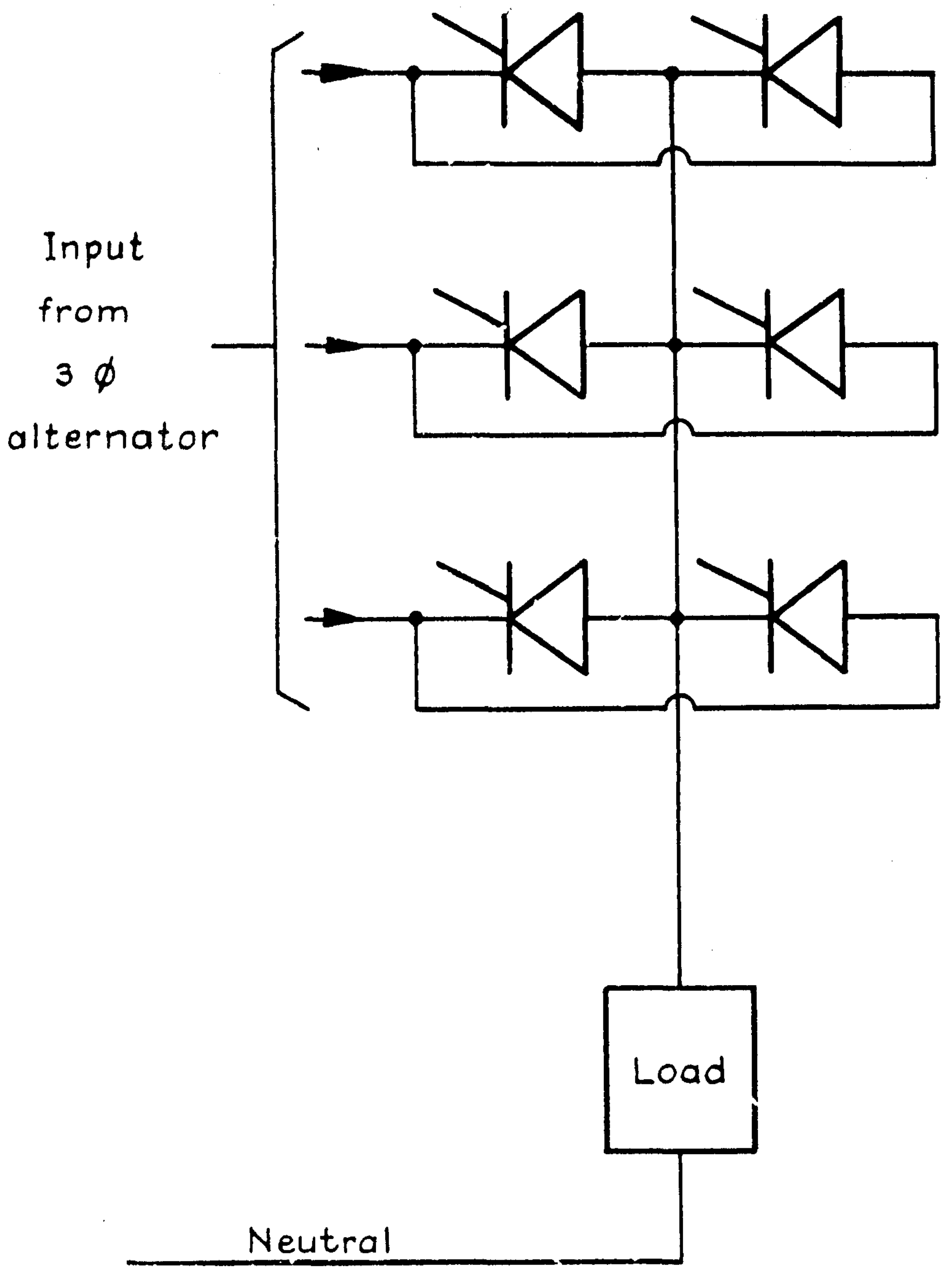


Fig. I Thyristor arrangement of a three phase half wave cycloconvertor

Fig. 2

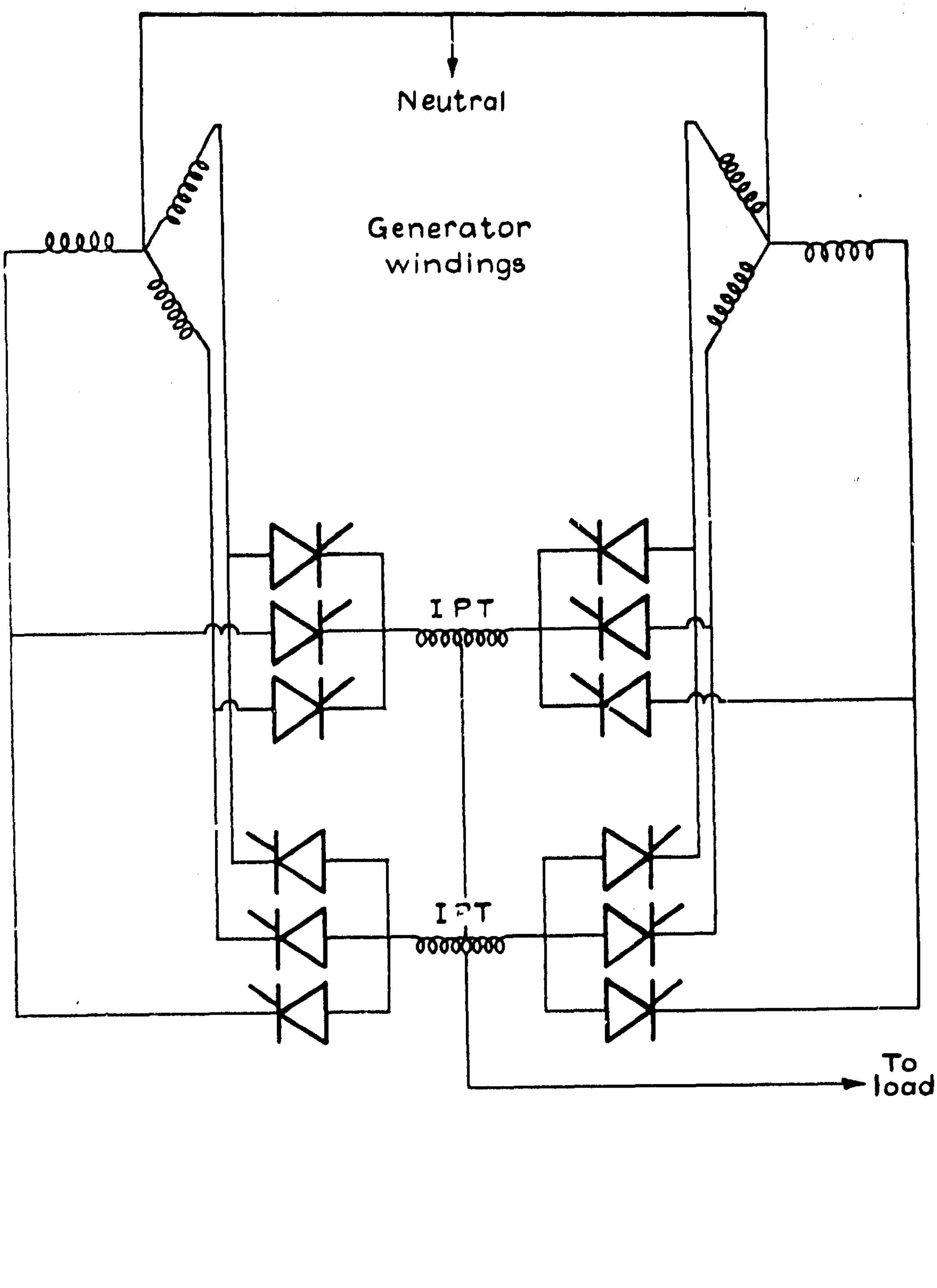
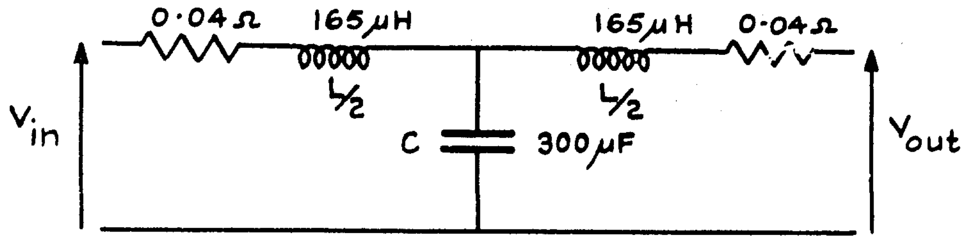
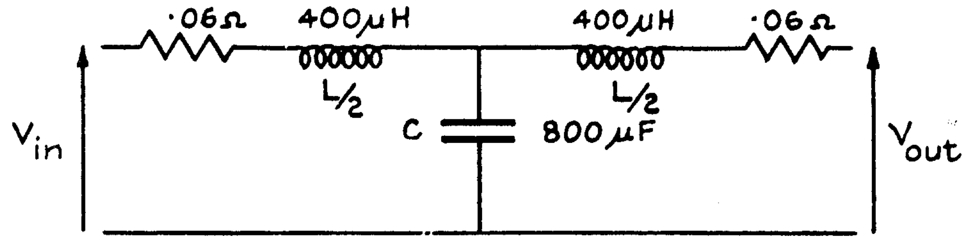


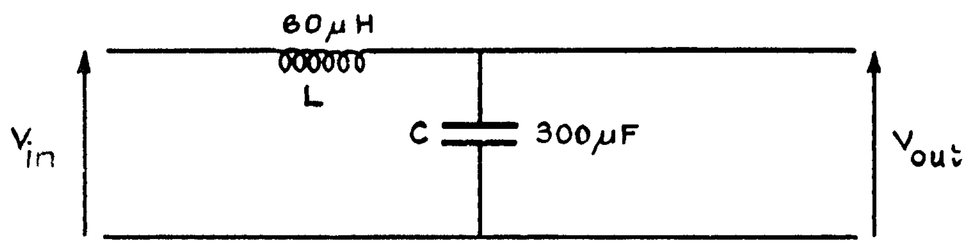
Fig. 2 Thyristor arrangement of a three phase double wye cycloconvertor with interphase transformers



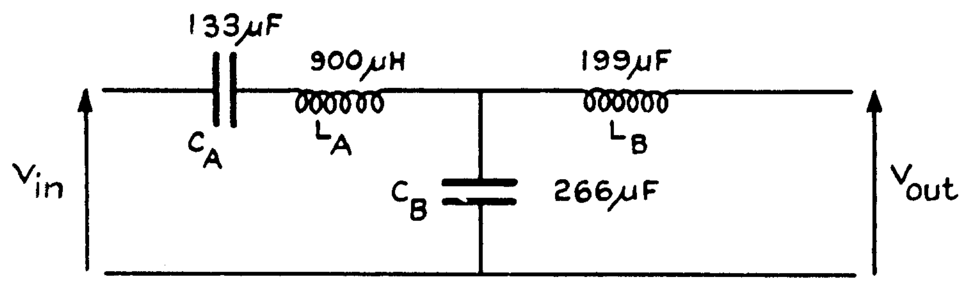
a T filter Mark I



b T filter Mark II



c L – section filter



d The Ott filter

Fig. 3 a – d Filter component values

Fig. 4

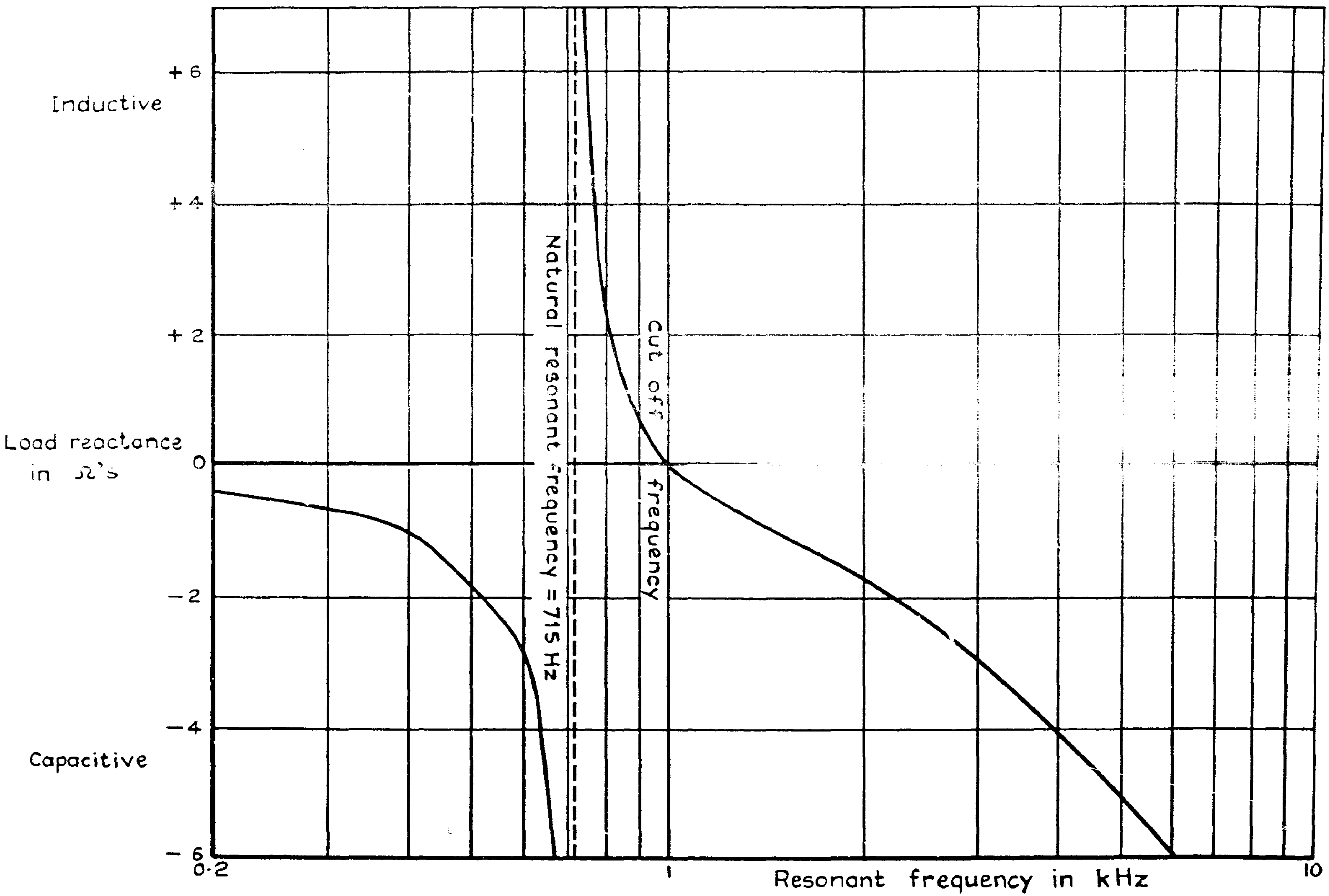


Fig. 4 Critical loads for the Mark I T-section filter

906644

TR 7108P

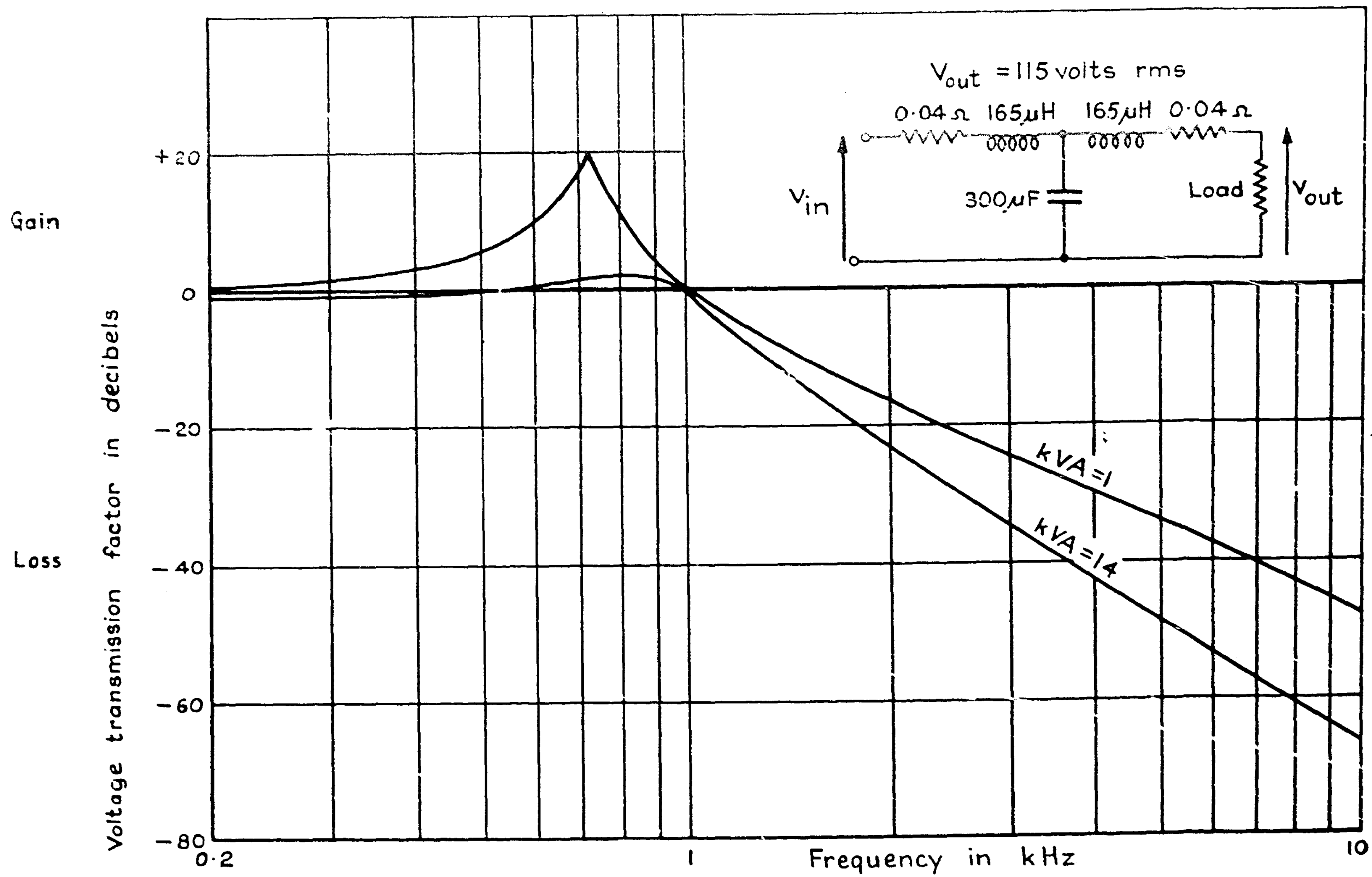


Fig. 5 Computed characteristics of the Mark I T-section filter, load 1·0 PF

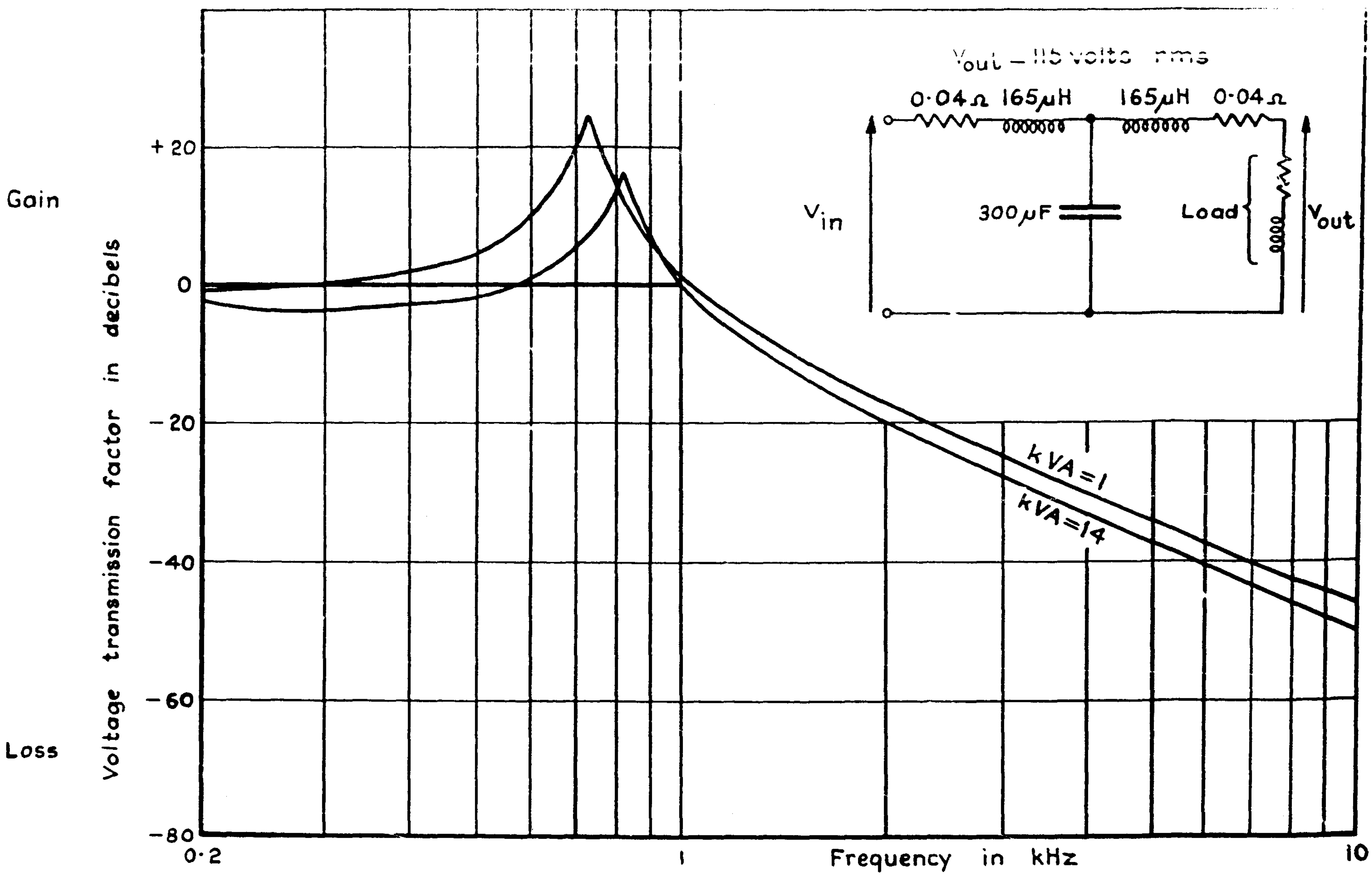


Fig. 6 Computed characteristics of the Mark I T-section filter, load 0·5 lagging

26648

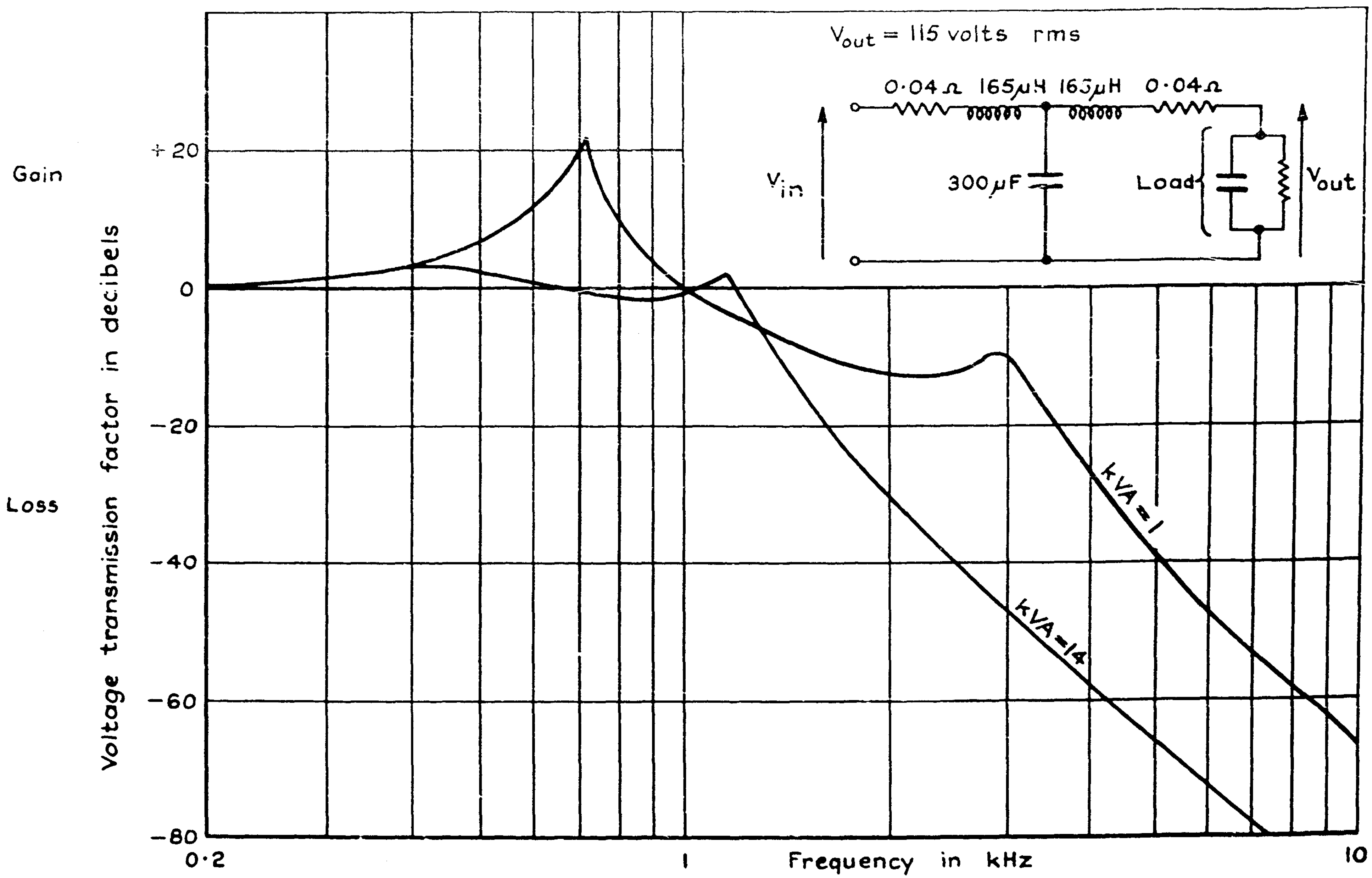


Fig. 7 Computed characteristics of the Mark I T-section filter, load 0·8 PF leading

Fig. 7

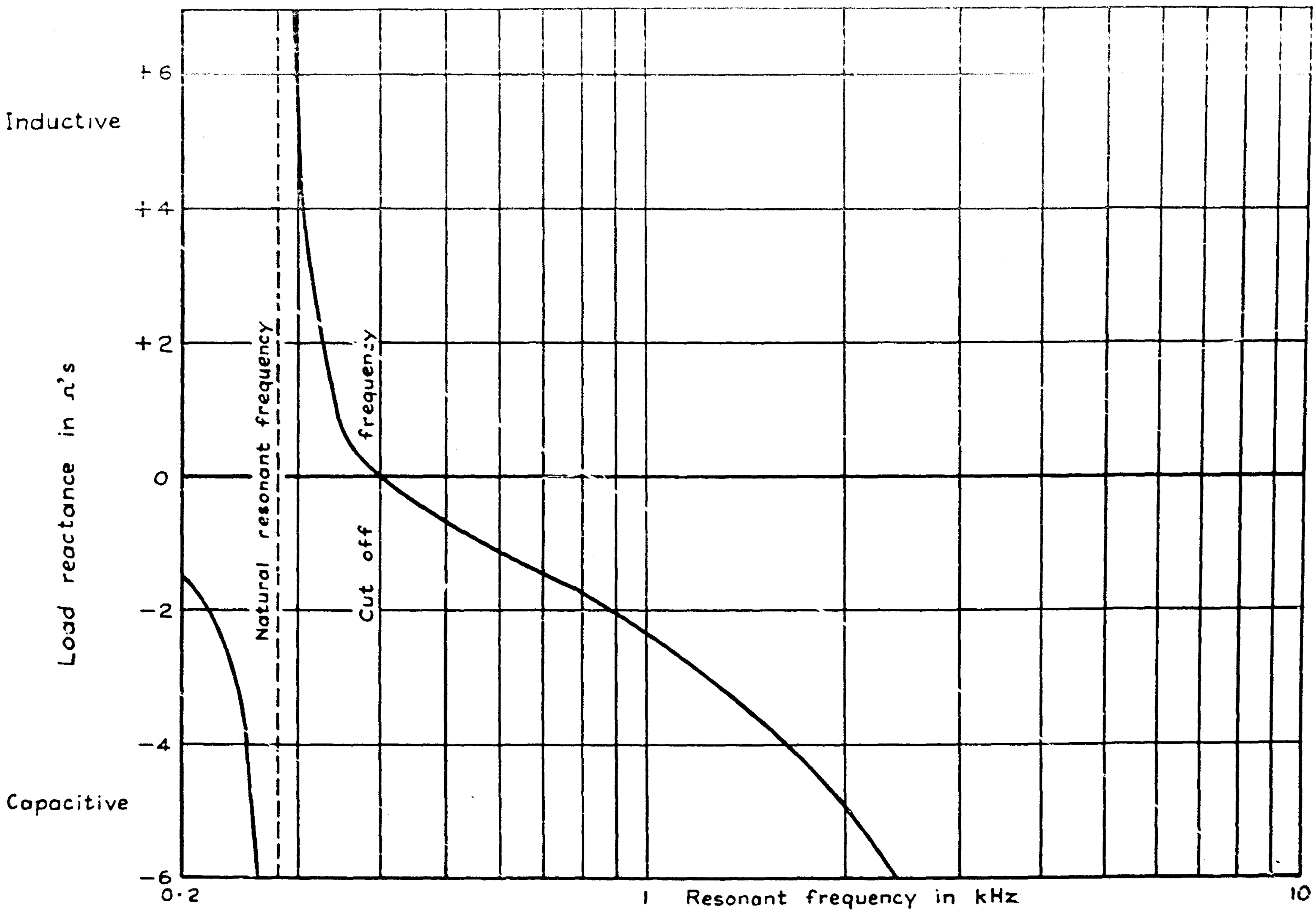


Fig. 8 Critical loads for the Mark II T-section filter

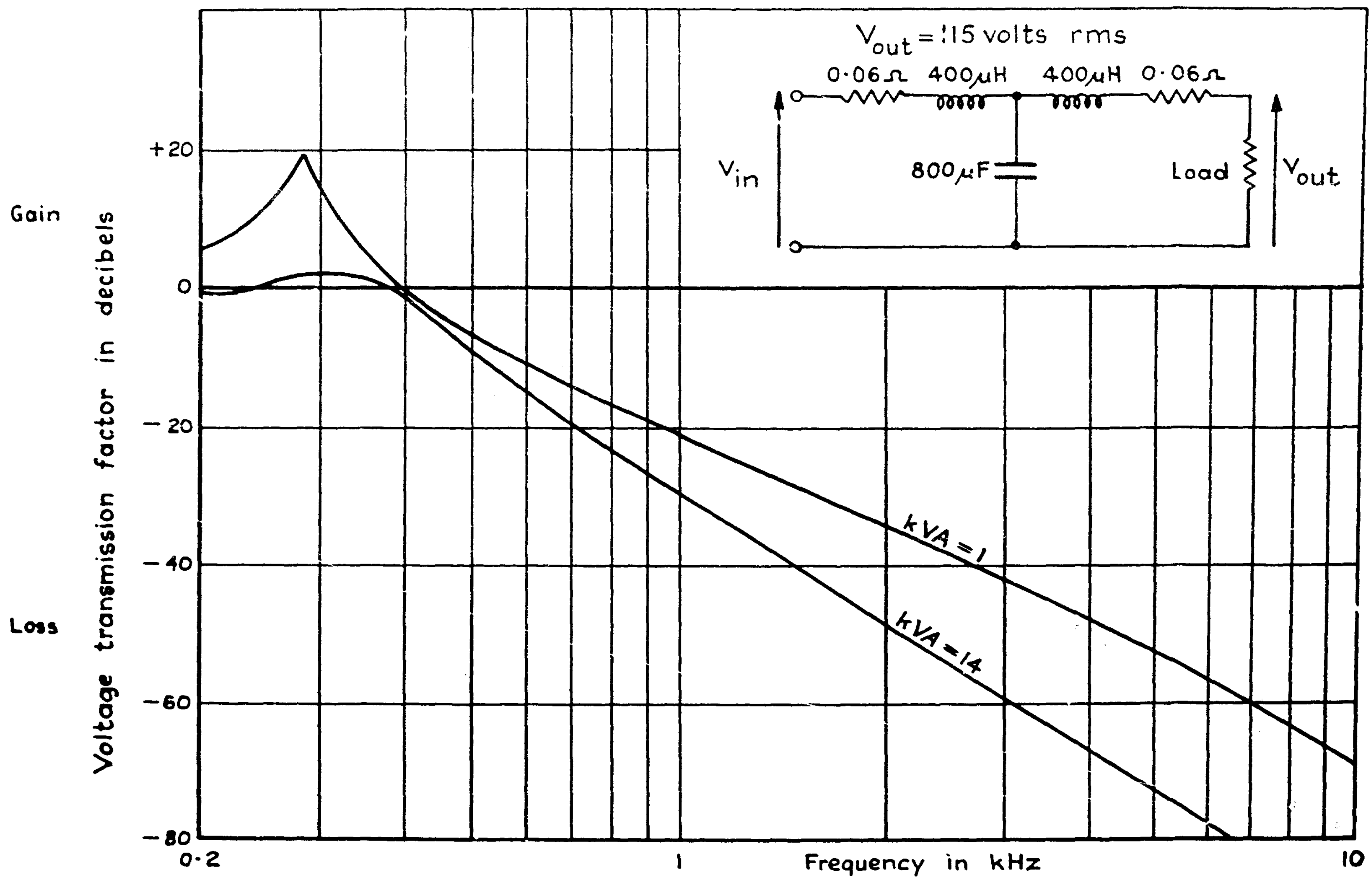


Fig. 9 Computed characteristics of the Mark II T-section filter, load 1·0 PF

Fig. 9

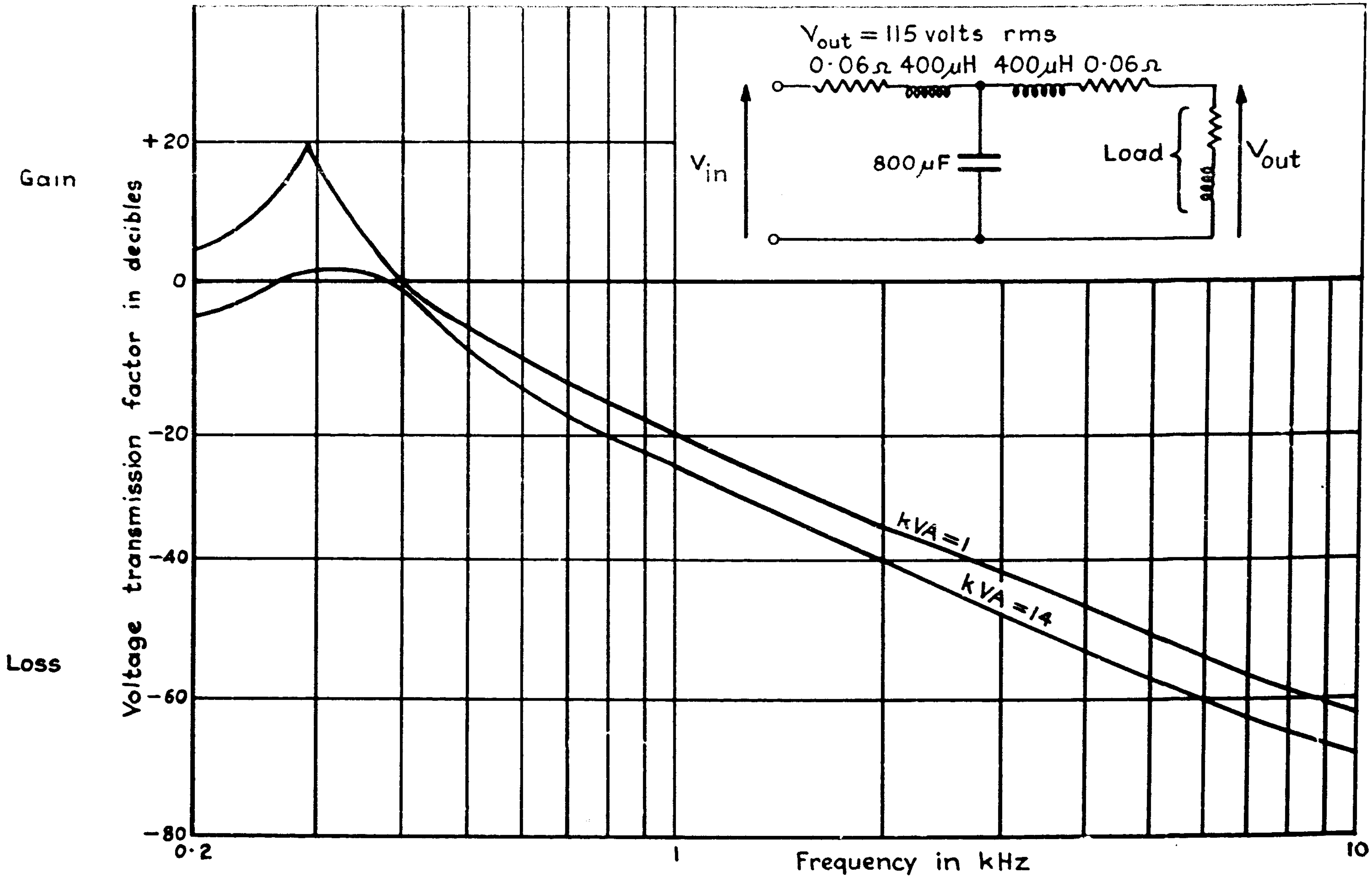


Fig. 10 Computed characteristics of the Mark II T-section filter, load 0·5PF lagging

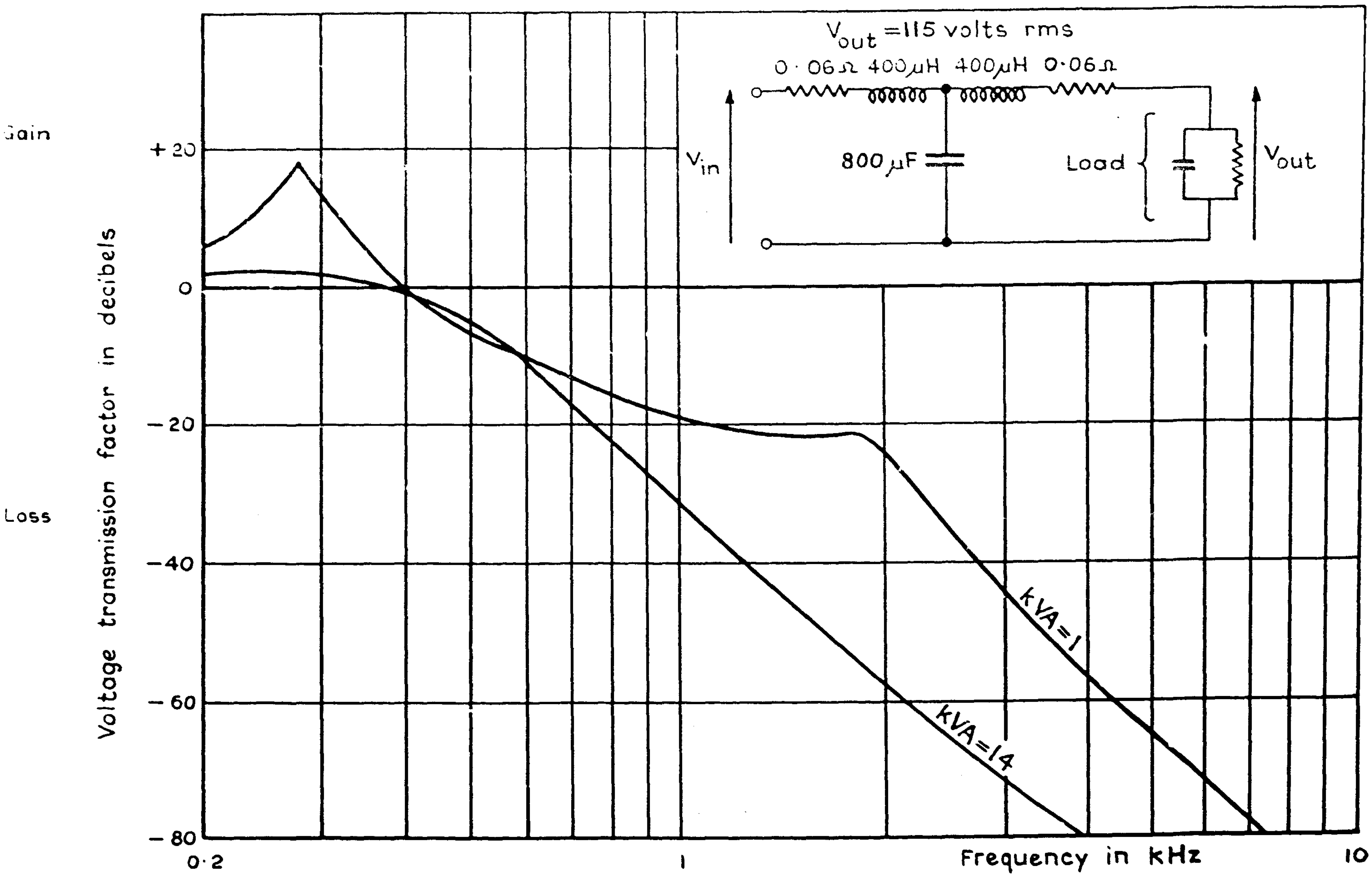


Fig. 11 Computed characteristics of the Mark II T-section filter, load 0·8 PF leading

Fig. 11

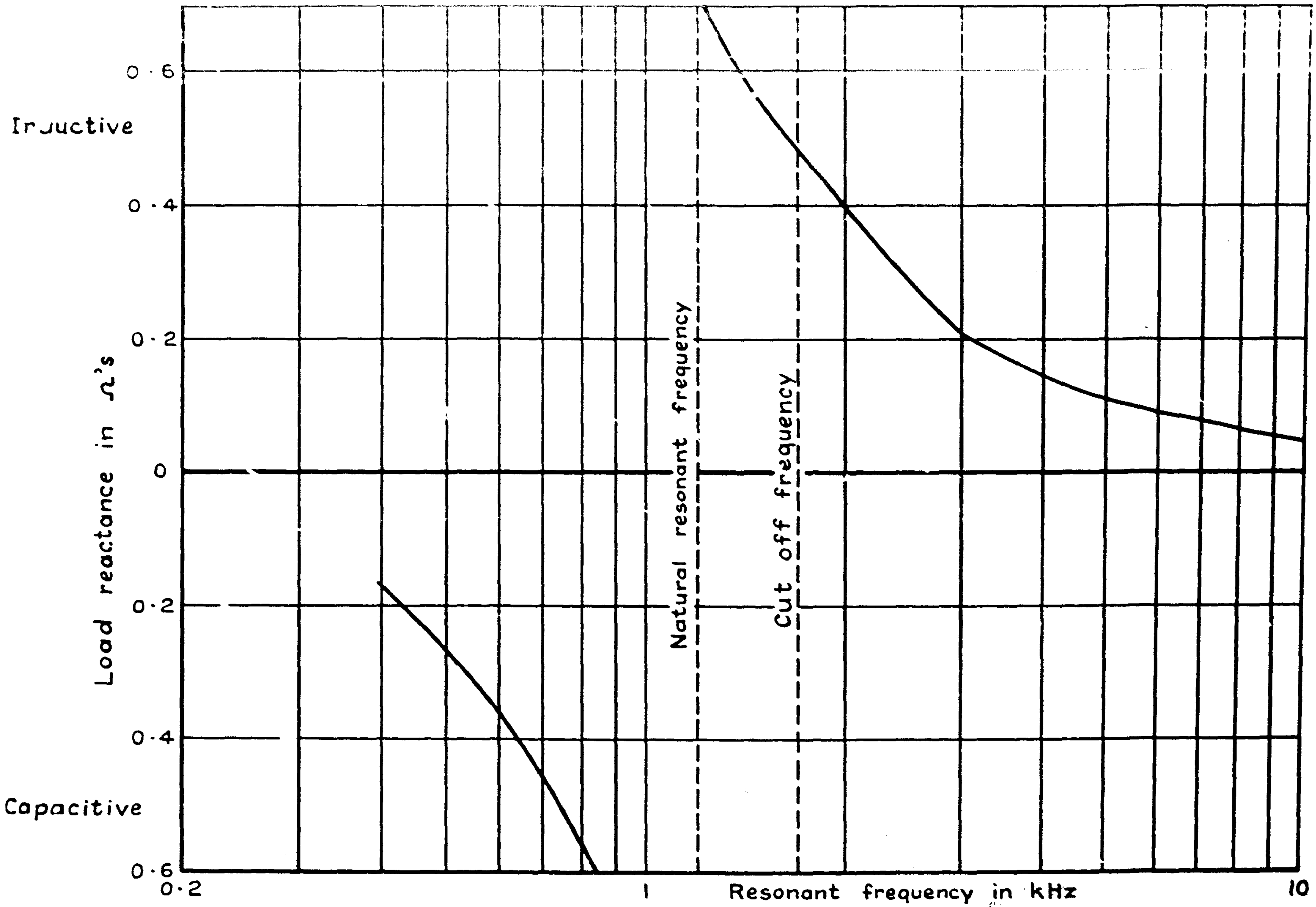


Fig. 12 Critical loads for the L-section filter

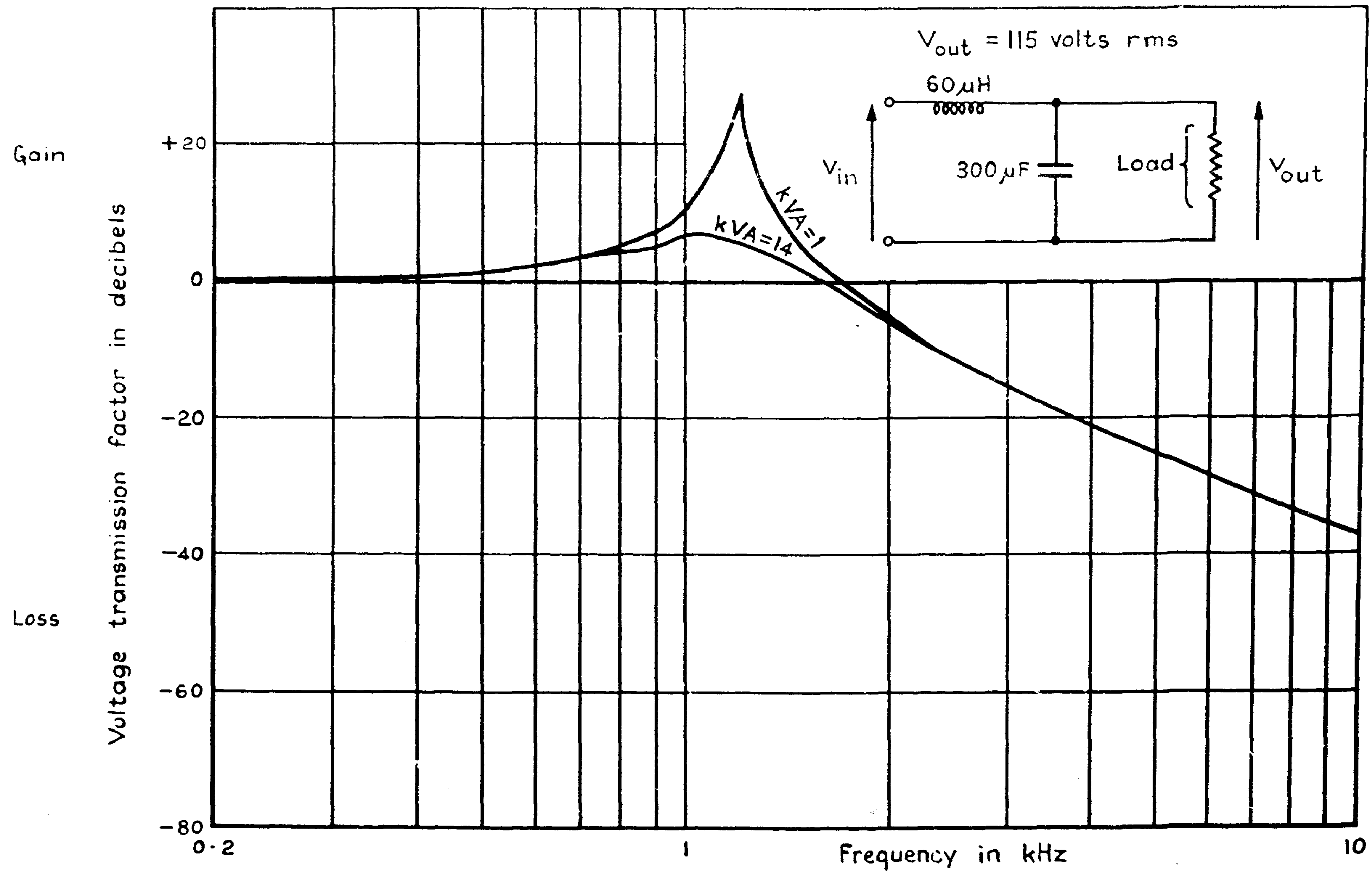


Fig. 13 Computed characteristics of the L-section filter, load 1·0PF

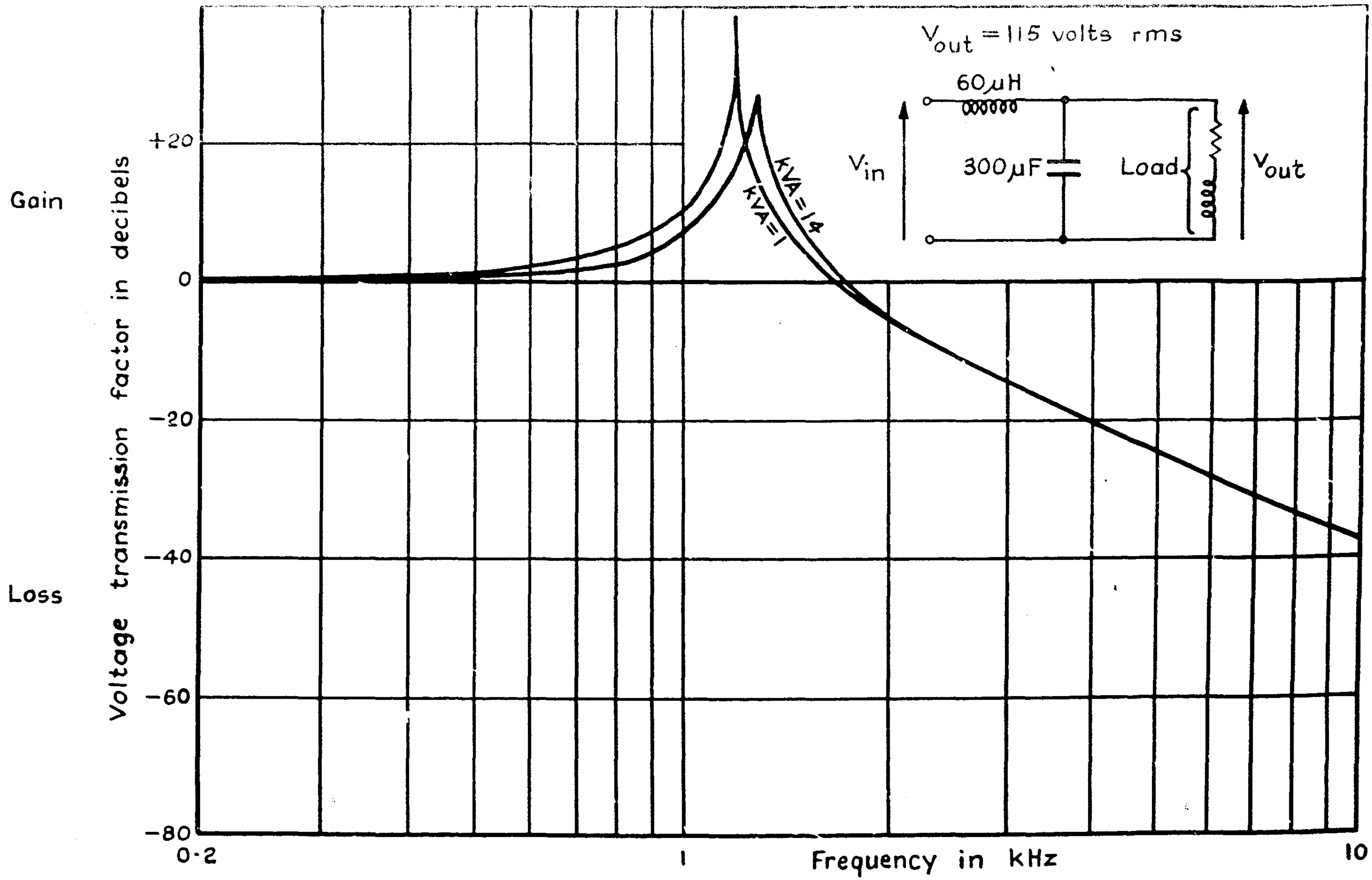


Fig. 14 Computed characteristics of the L-section filter, load 0·5 P F lagging

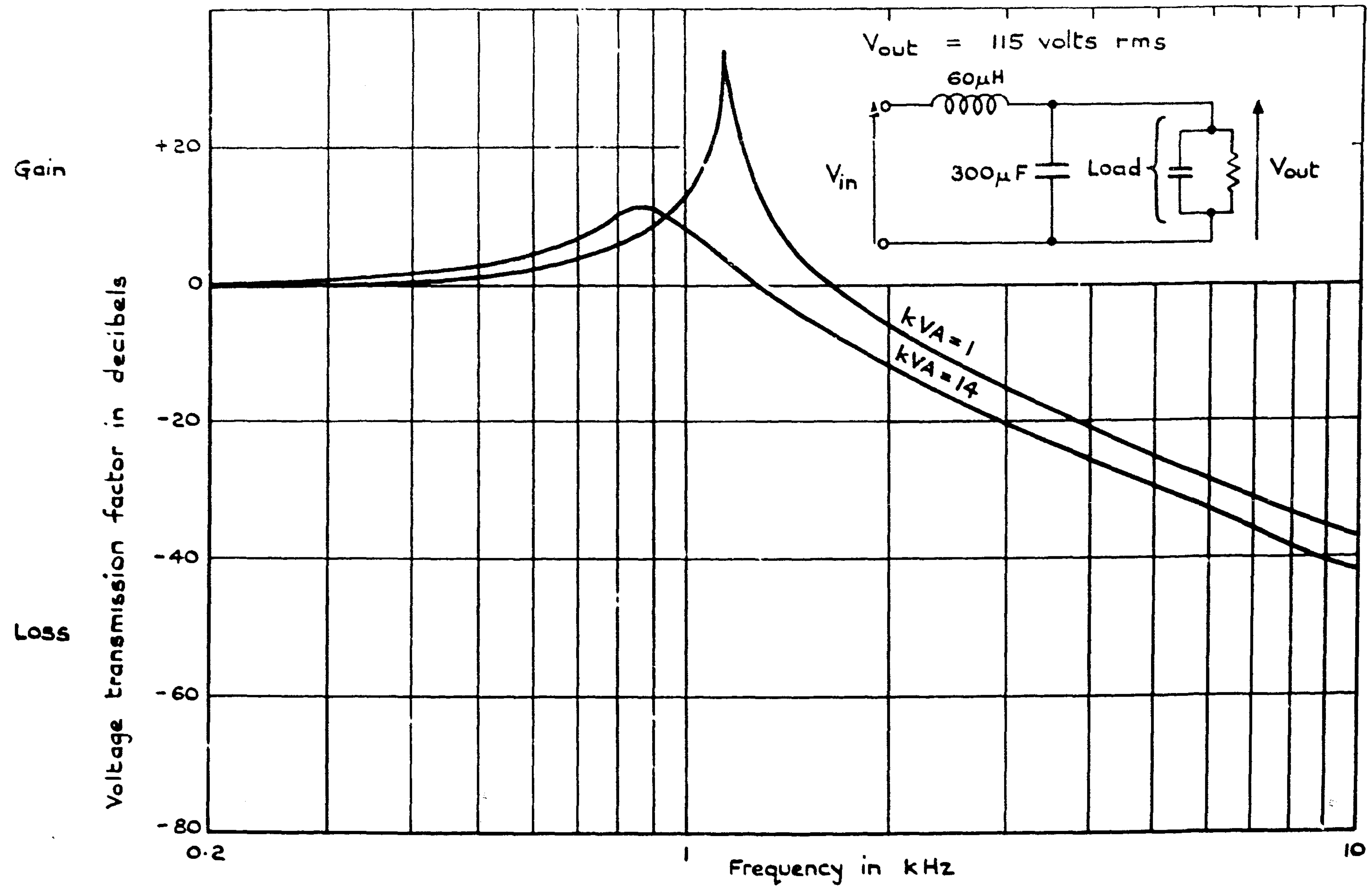


Fig.15 Computed characteristics of the L-section filter, load 0·8 PF leading

Fig.15

Fig. 16

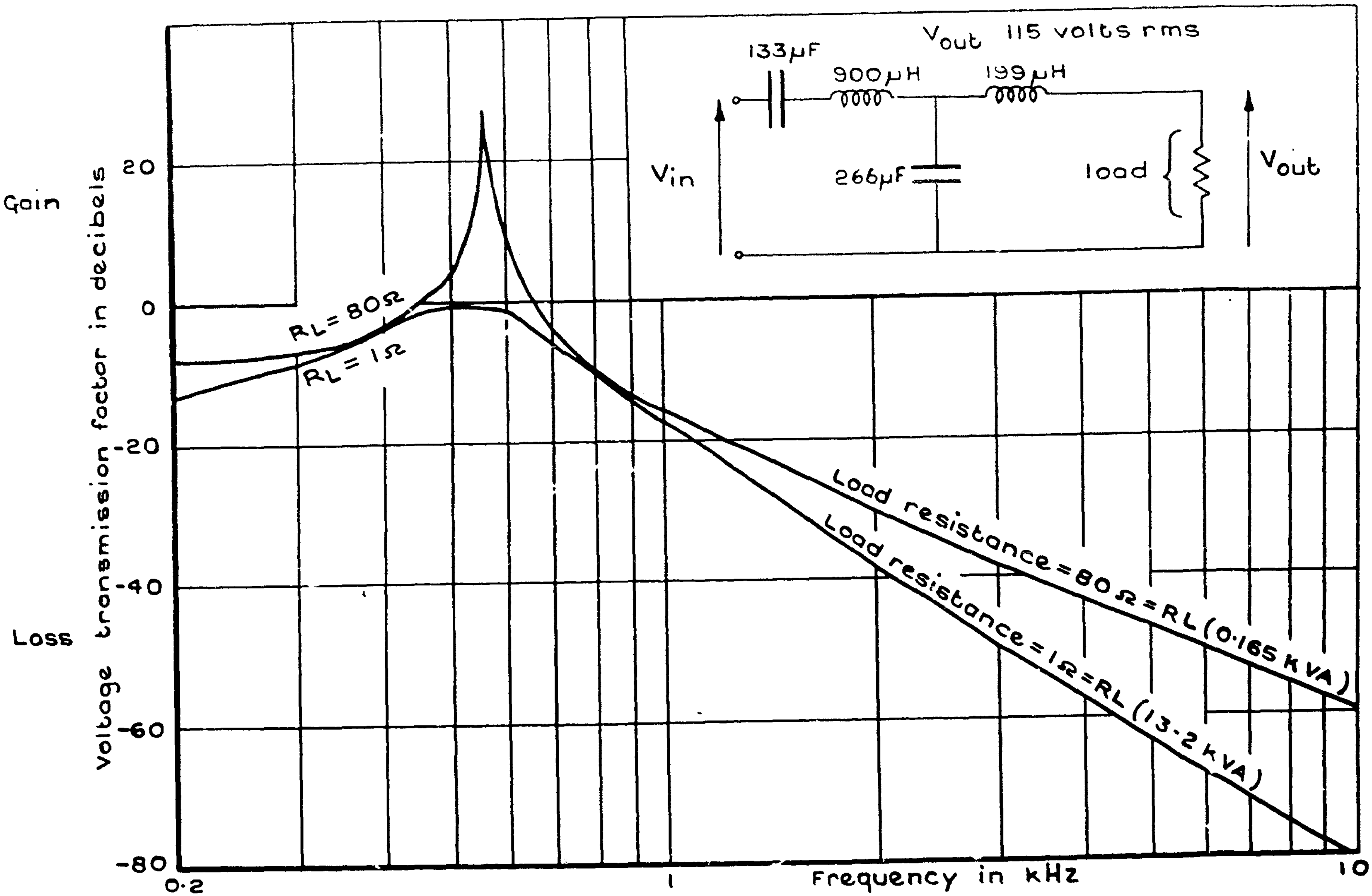


Fig.16 Computed characteristics of the Ott filter, load 1·0 P F

TR 71088

306656

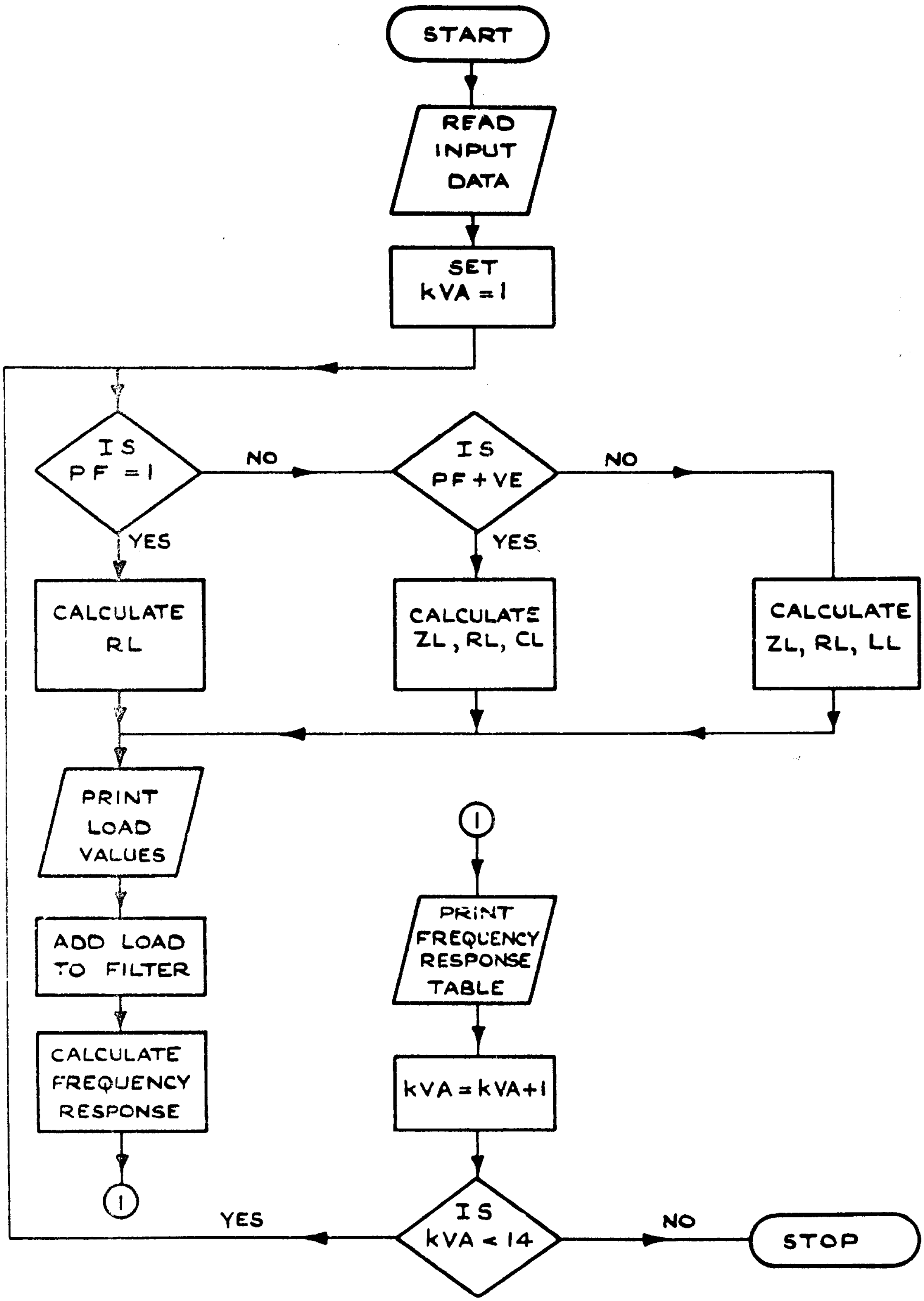


Fig. 17 Flow chart of frequency response program–EO99

TR 71088

906657

Fig. 18 & 19

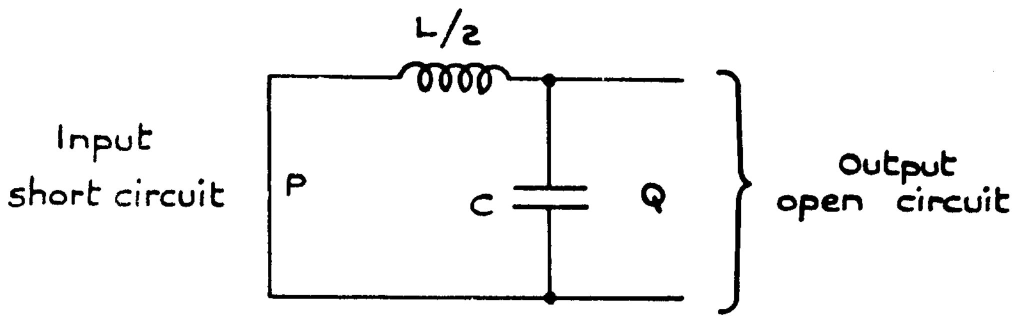


Fig.18 L section filter

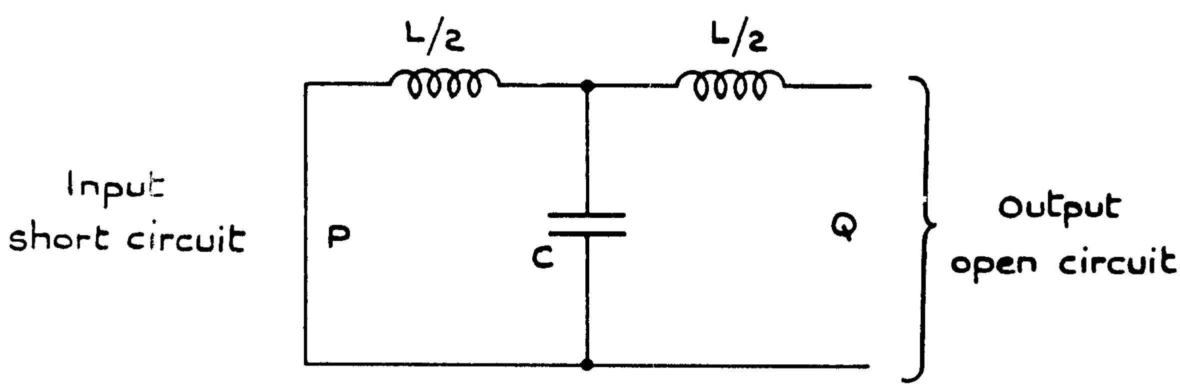


Fig.19 T section filter