The First Filter Choke—Its Effect on Regulation and Smoothing

By F. S. Dellenbaugh, Jr., and R. S. Quimby*

A POORLY smoothed power supply sounds like a sawmill. The analogy goes further as well. The first cut in a sawmill rips off the slabs and roughs out the log to its final shape. Further finishing operations each take a smaller and smaller slice. Ultimately the mahogany log of Honduras may become the highly polished piano or radio console. In the same way the first filter section roughs off the rectified a.c. and does the biggest job of trimming down the ripple to suit the exigiencies of the associated apparatus. It seldom requires polishing down as far as furniture, but added filter sections, like added woodworking operations, can be made to reduce ripple to almost any desired degree. As a result of this somewhat violent hacking off of ripple, it is found that the first choke of the usual type of filter used with Type '66 rectifiers has a very high a.c. potential across its terminals. "Very high" is used in the sense that this voltage may amount to about half the output voltage, while succeeding sections usually operate with a very low percentage of output voltage appearing as a.c. across the choke terminals.

This article is a continuation of the authors' discussion of high voltage filters that began in February *QST*, that article being essential to the proper understanding of the one herewith. The next of the series will appear in an early issue. — EDITOR.

For example, in the circuit shown in Fig. 1, operating at 1200 to 1400 volts d.c. across the load, the a.c. voltage across the first choke (from terminal to terminal of the choke winding itself) ran from 700 to 760 volts a.c., r.m.s. value. This voltage rises gradually as the load is increased, but in general may be assumed as about half the terminal voltage without serious error.

The inductance of a choke, for a given amount of d.c. polarizing current, is materially increased if the a.c. flux component is increased. (Provided that the sum of the d.c. and a.c. fluxes does not saturate the core.) This fact can be taken advantage of in the design of the first choke, resulting in economy of material, improved smoothing and, best of all, much improved regulation. It was shown in a previous article in *QST* [1] that the first choke has a critical value. If the inductance is greater than this critical value the output voltage becomes the average voltage of the rectifier output, "soaring" at low loads is avoided and the peak current in the '66 tubes is held to a minimum. Therefore let us set down the criteria for a first choke and see how near we can come to the ideal by special design.

1. The first choke will control regulation. For this purpose it must always have an inductance greater than the critical value; that is, very close to the load resistance in ohms divided by 1000, the quotient being henrys.
2. The first choke will control peak current in the rectifier. For this purpose maximum output allowable will be obtained when the choke has twice the critical inductance. This value will be referred to as the "optimum inductance."
3. The first choke will contribute to smoothing. For this purpose it must not introduce harmonics or instability, and must not resonate with the first condenser.
4. The first choke must adjust itself automatically to all loads. The desirable range will be from the "optimum value" at maximum current (minimum load resistance) to the "critical value" at minimum current (maximum load resistance).

CHOKE DESIGN

For discussion let us consider the circuit shown in Fig. 1, supposedly delivering 1000 volts d.c. to a resistance load. Regulation will be neglected for the present. A maximum current of 500 ma. will be considered as a safe overload limit, above the largest desired output. The minimum current will be taken as 50 ma., being either the bleeder current on a keyed circuit or the least probable current with a 'phone circuit. The range of the load resistance, therefore, will be 2000 to 20,000 ohms. Dividing these values by 1000, the limits of critical inductance are seen to be 2 and 20 henrys. But at the maximum load we want to be sure to reduce current peaks in the '66 tube, so here we must use the optimum value or 4 henrys.

Fig. 2 shows the limiting values of inductance below which we must not trespass for good operation. The critical inductance is drawn from 2 to 20 henrys as a straight line directly proportional to resistance and inversely proportional to current. The optimum inductance is placed at 4 henrys at 500-ma. load, twice the critical value. At the minimum load of 50 ma. the desired inductance can be the critical value; but we want a little leeway to be on the safe side, so 25 henrys is

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[1] Dellenbaugh and Quimby, *QST*, February, 1932.

arbitrarily picked as giving 25% more than the least allowable. The upper straight line is then drawn from 4 to 25 henrys, representing the practical threshold above which the choke should operate. The optimum value is only required at the maximum load, for as the load falls off in current — even though the ratio of peak to average current increases in the rectifier — the actual peak will not rise above the full load value.

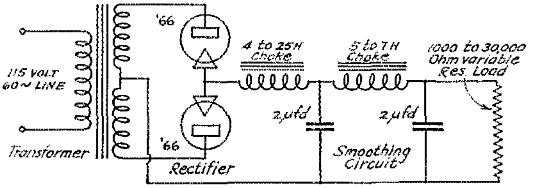

FIG. 1 — CIRCUIT DIAGRAM OF ARRANGEMENT USED FOR TESTS

It is well known that increased d.c. will reduce the inductance and that proper air gap will control such reduction in any given choke. Increased a.c. ripple through a choke will, as already mentioned, increase the inductance. The problem of design in the first choke is, then, to apportion the various parts so that the inductance will swing through the desired range. The air gap must be adjusted to the d.c. polarizing force so that the inductance will neither be almost lost at high currents nor flattened out to such an extent that inadequate inductance will result at very low currents.

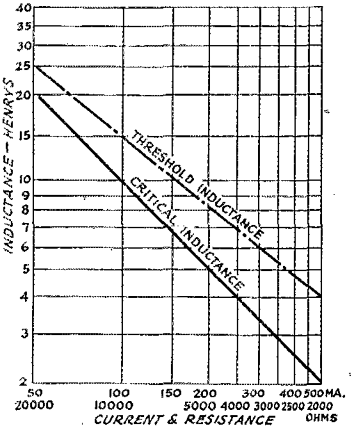

FIG. 2 — CRITICAL AND THRESHOLD VALUES OF INDUCTANCE

Output voltage about 1000, current range 50 to 500 ma.

Fig. 3 shows the behavior of a satisfactory first choke with different air gaps. The dotted curves represent the inductance values tested with a special bridge, the d.c. being as given at the bottom of the curve and the a.c. component being contributed by 1 volt a.c. across the choke. The inductance is measured in terms of the very small current resulting from this 1 volt a.c. impressed, and the resulting inductance values represent the minimum that will be obtained under almost any conditions. It will be noted that each curve touches the sloping straight line at a definite point. This point of contact, or tangency, represents the proper air gap setting for the maximum inductance that can be obtained with the particular core, winding, a.c. and d.c. for which the curve is drawn. From this it is evident that the curve for an air gap of 0.02 inch will give 4 henrys at 500 ma., but will only rise to a value of about 10 henrys at 50 ma. This is the point where we begin to give thanks for the large a.c. voltage across the first choke, and before going any further this effect upon choke behavior must be considered.

First look at Fig. 4. Here the increase of inductance above the 1-volt value is shown. The a.c. voltage is about 600 to 700, the inductance having been measured in an actual circuit similar to Fig. 1 by means of a lot of trick blocking chokes and by-pass condensers. Therefore the accuracy of the results cannot be guaranteed, but the general trend is close to actual facts. It will be seen that the percentage increase of inductance is greatest at low values of d.c. and falls off as the d.c. increases. This tends to increase the range through which the choke will operate. Referring back to Fig. 3 this can be represented by drawing straight lines parallel to the first solid heavy one, as shown by dashed lines marked "500 volts" and "1000 volts." These will be more or less parallel to the original line obtained from the bridge tests, and the dotted-line curves of inductance will rise towards these upper lines as the impressed a.c. voltage approaches corresponding values. They will, however, rise more at the low current end than at the high current end, as indicated by Fig. 4.

Taking the inductance curve for 0.01-inch gap (Fig. 3) and raising the inductance by the percentages of Fig. 4, the high current end rises almost to 4 henrys, while the low current end rises to 25 henrys. Therefore it looks as though this choke with a gap of about 0.01 inch would perform just about as we want it to in an actual circuit. The next thing is to try it and see what happens.

COMPLETE CIRCUIT BEHAVIOR

The choke discussed above is now placed in the circuit of Fig. 1 and the first choke and the gap adjusted until the desired results are obtained. Fig. 5 shows the inductance relations that actually occurred. The current and corresponding resistance values are shown at the bottom of the curve. The two lines of critical and threshold values of inductance are repeated from Fig. 2 for reference. The actual first choke inductance is shown by the solid heavy line. The best air gap was found by trial to be 0.012 inch. This being a little bigger than the value of 0.01 inch discussed above, it resulted in the inductance being a little higher than anticipated at full load and a little lower at light load; but the criterion of maintaining optimum inductance at full load and not less than critical inductance at minimum load was satisfied.

The effect of other air gaps markedly different from the best one is interesting. If the gap is made much larger, the inductance flattens out and is represented by the curve marked "Large Air Gap" in Fig. 5. With this setting the inductance crosses the line of critical inductance at about 160 ma., at the point marked "C." Above this value the regulation will be satisfactory, but for smaller currents the voltage will begin to "soar." This same inductance crosses the threshold inductance at a little more than 300 ma. and so protects the '66 tube by reducing peak current at higher currents. Thus such a choke would be satisfactory on a few counts, but not all.

If the gap is too small very violent instability may occur at some particular current range. The inductance curve of Fig. 5 marked "Very Small Gap" saturates and tends to cross and recross the line of critical inductance at the points "A" and "B." As this point is reached when increasing the load current slowly, the choke inductance drops below critical value, the output voltage begins to soar and, consequently, the current begins to increase. This increase in current pushes the inductance still lower, with consequent further voltage rise. At a higher current the inductance again becomes greater than the critical; the output voltage finds itself up in the air, too high for the instantaneous conditions, and it collapses, the whole cycle repeating rapidly over and over. The results are very startling. Everything hums violently, the load concentrates almost entirely in one rectifier tube, the voltage across the choke rises to a higher value than almost any other voltage in the circuit. Increasing the air gap seems always to cure the instability. Apparently when such conditions exist the magnetic cycle followed by the choke core deviates materially from normal, a definition of its inductance under the circumstances seeming to be impossible. This horrible behavior is mentioned as a warning against too small gaps. But with the correct characteristics shown in Fig. 5 the results are entirely normal, stable and very advantageous. With a keyed circuit this instability is not encountered if the two currents, with key closed and open, lie outside the unstable range. For 'phone operation the circuit should be tested carefully for such instability to avoid its occurrence when actually on the air.

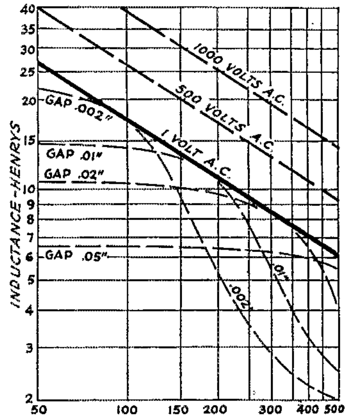

FIG. 3 — VARIATION OF CHOKE INDUCTANCE WITH CURRENT AND AIR GAP

Heavy line is maximum inductance possible for given current for fixed air gap. Straight dashed lines show effect of increasing a.c.

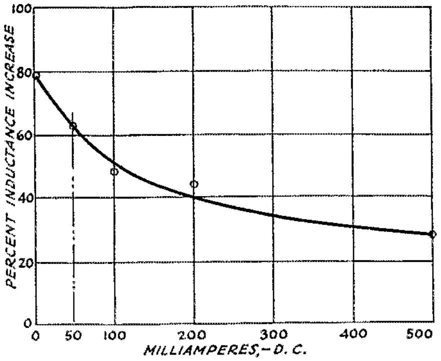

FIG. 4 — PERCENTAGE INCREASE OF INDUCTANCE FOR HIGH VALUES OF IMPRESSED A.C.

The a.c. voltage was approximately the same as encountered in actual circuit operation. The reference inductance is that obtained by bridge methods with rated d.c. and 1-volt 60-cycle a.c.

ACTUAL REGULATION

The proof of the pudding is in the eating. This discussion so far has attempted to build up the reason why and the designs showing how good regulation may be obtained. Fig. 6 shows the overall regulation actually obtained. The circuit of Fig. 1 was used, the first choke being the one described above and the condensers each 2 μfd. The second choke was relatively small, although it gave adequate smoothing, varying from about 5 henrys at full load to some 7.5 henrys at 50 ma. These are actual measured values, certainly accurate to better than 10%, and not nominal name-plate ratings. The load consisted of tabular slide-wire resistances. The power transformer was specially designed for good regulation but is in no way abnormal or grotesque, being of about customary size and weight. The resistance of the two chokes was also about normal, being 60 to 70 ohms each.

The voltage drop is marked off (Fig. 6) for a full load of 350 ma. as representing customary amateur practice. The regulation curves were carried out to the full current limit of the rectifier tubes, however, to see whether the regulation would break at overloads. The results with this circuit are obvious from the curves, which speak for themselves. At a little less than 50 ma., where Fig. 5 shows the first choke rapidly reaching the critical value, the voltage begins to rise as is to be expected. Since the previous article considered only the filter circuit, it might be worth emphasizing that this regulation is actually the output voltage with the complete circuit operating upon a normal 115-volt 60-cycle supply line. The voltage drop includes transformer regulation, tube drop, choke resistance drops and any effects of changes in wave shape with load.

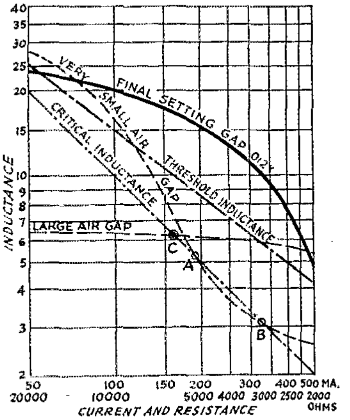

FIG. 5 — INDUCTANCE OF SWINGING CHOKE IN ACTUAL CIRCUIT

Critical and threshold inductance lines are repeated from Fig. 2. The two broken line curves show the effect of too large and too small an air gap.

Fig. 7 shows for comparison a filter circuit where the first choke has substantially constant value. The circuit was exactly the same as before except that the first choke was replaced by another. In the upper curve a 3.5-henry choke was used, with a very large air gap so that its inductance remained almost exactly constant. This would reach the critical value at a load resistance of 3500 ohms, or about 340-ma. load current with the voltage obtained. It will be seen from the curve that the voltage starts to rise at just about this point. The other curve was made with a slightly larger first choke, of about 5 henrys. The critical load resistance for this choke is about 5000 ohms, or 250-ma. load current, and again the voltage begins to soar at just about this point.

It is worth noting that the voltage at full load of 350 ma. (or higher) is exactly the same with all three first chokes on the same transformer voltage; but with the "swinging" first choke, soaring is prevented and regulation much improved without sacrifice of actual operating voltage.

It is possible to adjust a properly designed first choke so that its inductance will be above the critical value for low current and saturate to a value below the critical for high current. In this case the voltage might actually rise for the larger currents, and a compounding effect be obtained.[2] There are two very serious objections to this arrangement, however. First, the choke is inadequate to limit the current peaks in the rectifier, which is one of its most important duties, and these peaks would be excessive at full load, the very time when they should be reduced as much as possible; and second, instability of operation as described above is difficult to avoid. There are, of course, other methods of improving regulation[3] but this article is concerned only with straight filter design and the improvement of regulation by the inherent characteristics of the filter elements themselves, regardless of auxiliary aids.

FILTER HUM

Having started with a sawmill, we shall end with the polish. In the test circuit used, in spite of the small second choke, the hum was within the limits usually found satisfactory in amateur operation. Little data are available on this point, satisfaction being obtained by practice rather than experiment. However, it is possible to compute ripple with a fair degree of accuracy; and smoothing circuits reported as satisfactory indicate the criterion to be a ripple voltage of about 1% of the d.c. output. The table below

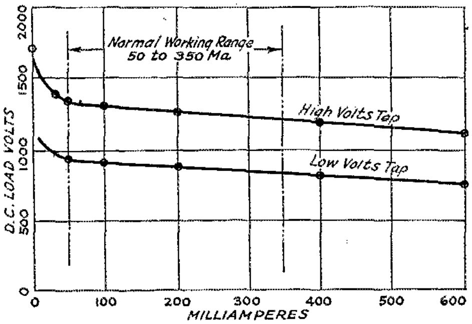

FIG. 6 — REGULATION ACTUALLY OBTAINED WITH SWINGING CHOKE AND CIRCUIT OF FIG. 1

Normal load considered to have range of 50 to 350 ma.

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[2] Glaser, "Improving the Voltage Regulation of Rectifier-Filter Systems," *QST*, October, 1931.

[3] A "voltage-regulating transformer" method is also described by Glaser.

The load consisted of tabular

shows the actual volts of ripple obtained, as measured with a vacuum tube voltmeter. These are a.c. (r.m.s.) voltages. They are all under the 1% criterion with the exception of the maximum current which was slight overload, above 350 ma.

Rectifier Input Volts per Side, a.c.	D.c. Output		Ripple		
	Volts	Ma.	Measured Volts.	Calculated Volts [4]	Per Cent of Output
1050...	925	100	3.0	2.7	0.33
1050...	890	200	3.5	3.7	0.39
1025...	860	300	5.1	5.3	0.59
1000...	840	400	9.3	8.8	1.10

[4] See Appendix.

SUMMARY

We started out to design a first choke in the usual type of circuit used with '66 rectifiers which would combine as many functions as possible, taking advantage of the peculiarities of the circuit to produce desirable results. These functions may be tabulated as follows:

1. To improve regulation.
2. To limit peak current in rectifier tube.
3. To contribute materially to smoothing.
4. To provide automatic adjustments for varying loads.

All of these results can be accomplished by the proper adjustment and design of the first choke. The regulation, including all losses of voltage from the supply line to the load terminals, can be made less than 10% of average output voltage over the working range of 50 to 350 ma. The peak current is limited to very little more than the average (d.c.) load current, allowing maximum output without overloading the tubes. The choke contributes to smoothing and satisfactory results are obtained with only a 5- to 7-henry choke as the second filter inductance. The inductance swings automatically for changes in load so that it exceeds the desirable threshold inductance value from 50 ma. to 500 ma.

A first choke of this type will be much smaller than one designed for substantially constant inductance of the maximum value required. The only difficulties to be avoided are instability due to too small an air gap and resonance with first filter condenser. With condenser sizes in general use this latter difficulty is not likely to occur.

A first filter choke of this swinging type can be added to any existing filter circuit without difficulty and should improve operation materially.

APPENDIX

Voltage ripple for full-wave rectification can be calculated approximately for circuits such as Fig. 1 by means of the following formula:

$$\text{Volts (a.c., r.m.s.) ripple} = \frac{5.3E}{L_1L_2C^2}$$

where supply line is 60 cycles,

E is transformer secondary voltage per side,
L_1 is first choke inductance, henrys
L_2 is second choke inductance, henrys
C is total shunt capacitance, μfd.

The inductance values for calculating the ripple were taken as follows (from actual test curves):

Ma.	L_1	L_2
100	19 h.	6.8 h.
200	15 h.	6.3 h.
300	11 h.	5.8 h.
400	7.6 h.	5.0 h.

These data are only correct when smoothing to 5% or better, and when any L and C resonant frequency is less than one-half of 120 cycles. The constant (5.3) assumes that 60-cycle full-wave balanced rectification is used. This covers the majority of satisfactory filters in use. For poor smoothing the actual ripple will be much greater than that indicated by the formula.

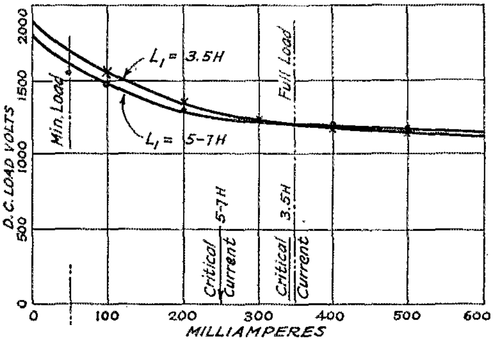

FIG. 7 — REGULATION OBTAINED WHEN FIRST CHOKE IS OF FIXED INDUCTANCE

The voltage rises rapidly when the current falls below a value corresponding to the critical condition for the first choke employed.

Strays

G6TP and G6NI have been working two-way over a distance of 15 miles on 2½ meters. Both 'phone and c.w. are used.

Prof. Myres, W8AJK, of West Virginia University, has discovered a new way to QSY with crystal. He finds that dropping a crystal on the floor a sufficient number of times will eventually cause it to become several smaller crystals whose frequencies seem to be slightly different. W8TI's coöperation in contributing crystals made the experiment possible.