The Important First Choke in High-Voltage Rectifier Circuits

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

A KNOWLEDGE of circuit behavior is all important in experimental engineering. Michael Idvorski Pupin called this "the physical conception" of engineering. More recently, Johnson O'Connor of the General Electric Company has defined it as "space visualization." In any event it is almost imperative to know, feel or imagine what is going to happen in a given set of circumstances. Theory is invaluable as a guide but is based upon prior observation, while experimental work is the proof of the engineering pudding. Guglielmo Marconi, whose thirtieth anniversary of transatlantic radio is being celebrated even as this is written, succeeded because he tried to see what would happen even though Hertz had shown that radio waves travel in straight lines and theoretically would not follow the curvature of the earth.

Dr. Dellenbaugh's name has been closely identified in amateur circles with the design of electrical filters from the time of *QST's* publication of his classics on filter design back in 1923. Their popularity demanded reprinting in abstract form; and the tabulated data for filter design that appear in *The Radio Amateur's Handbook* to this day have been inherited from them. It is with real pleasure, therefore, that *QST* presents this article as the first of a series by the same Dr. Dellenbaugh, in collaboration with Mr. Quimby, treating the filter problems peculiar to modern rectifiers. — EDITOR.

In straight a.c. and d.c. circuits, under conditions of continuous current flow, space visualization is not difficult and comes unconsciously to successful experimenters. It seems perfect common sense, for example, to visualize that if the voltage is increased, the current will increase. Meters put in the circuit give consistent readings and their meaning is usually clear. We know that a d.c. meter will not measure a.c. and that most a.c. meters will operate in either an a.c. or d.c. circuit. But very few people mentally connect up the fact that a meter is merely indicating some sort of average of instantaneous values. As long as the wave shape is normal, as it is in substantially all power circuits, the meter readings behave; meters in series give similar readings even if dissimilar in type and the ordinary laws of power, current, voltage and impedance relations hold good.

PECULIARITIES OF RECTIFIER CIRCUITS

When dealing with circuits containing rectified a.c., however, the situation is very different. At first glance various meter readings appear to be inconsistent. The circuit is not subject to ordinary mathematical analysis due to the discontinuous action of the rectifier itself. The current never reaches the same continuous flow as in the usual power circuits, since the alternate opening and closing of the circuit through the rectifiers renders the final current as a summation of successive transients. It is difficult at best to visualize transient phenomena and when complicated by rectifiers, which may conduct or shut off at any point in the cycle as a result of the transient voltages set up by the various circuit elements, a mental picture of what is happening is well nigh impossible. The only way to get around this difficulty is to play with various simple circuits, building up step by step the practical combinations required, and to observe all the events taking place by means of special tools such as an oscillograph to show wave shape, stroboscopic devices to study particular portions of cyclic operation and many accurately calibrated meters.

Unfortunately such tools are not usually available to the amateur and exist largely in the laboratories of scientific institutes and manufacturers. The scientific institute in turn experiments from the academic point of view, usually involving somewhat abstruse and mathematical theory in their pursuits. This is in no way derogatory to these institutions; it is very valuable work of a pioneering nature, but usually is not available, or else is incomprehensible, to most amateurs. It appears, therefore, to be the duty of the manufacturer with adequate equipment of this nature to interpret researches along new lines so that they will be useful to the amateur, as well as to manufacture apparatus that will fit advantageously into such circuits and devices as advances in the art produce.

The recent rapid increase in the use of high-voltage rectifiers, such as the Type '66 and similar tubes, has introduced the necessity of so designing circuits that they will not only produce the desired d.c. voltage with low ripple but will also protect the rectifier tube as well. This type of tube is limited by peak current and peak inverse voltage. Ordinary meter readings indicate some sort of a "funny" average and nobody

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can guess what the peak current is from the reading of one meter. For the sake of the meticulous minded it might be added that peak values do bear a definite relation to meter readings *for uniform and known wave shape*. The whole theory of a.c. is built on this basis. But a knowledge of wave shape is imperative. The usual relations assume it to be known and from this we derive relations and factors which we assume to be facts. When wave shape becomes erratic, as in rectifier operation, a detailed oscillographic study is necessary for interpretation.

It has become common knowledge, among those interested, that a choke must precede the first condenser in the filter circuit used with such high-voltage rectifiers.[1] This choke is required to reduce the current peaks. This much qualitative information is available. But further questions are: How much does such a choke reduce the peaks, what size has it got to be, how are we going to know whether the tube is operating within safe limits or not? In other words, to properly design the circuit for the best use of materials, for maximum output safely allowable and for the least cost, quantitative information is required. With all due respect to other authors on the same subject, this point of design seems to be still rather hazy and full of compromises. It is the purpose of this article to show that the inductance of the first choke has a very definite critical value, depending upon the load resistance only, and to describe several tests illustrating what happens when the inductance of the first choke is varied.

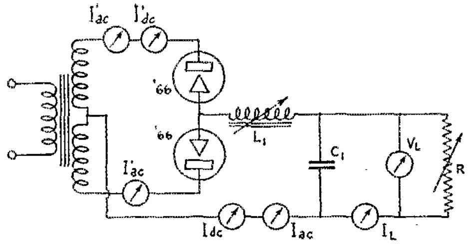

FIG. 1.—TEST CIRCUIT WITH INCOMPLETE FILTER

THE SET-UP FOR THE TESTS

The purpose of the circuit elements of a smoothing filter is to store up energy during voltage peaks and deliver it during voltage valleys. The inductance elements store this energy in the form of electric inertia by means of their magnetic field. The condenser elements store energy in the form of electric elasticity in their voltage fields. Therefore we are dealing with electric weights and springs, a definite analogy frequently of use in visualizing circuit behavior. It is known that as the first inductance is made greater the peak current becomes less. A guess can therefore be made that there must be some relation between the first inductance element and the constant energy being withdrawn through the load. At the risk of criticism for being mathematical, we may state that:

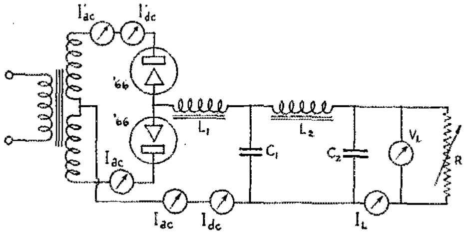

FIG. 2.—TEST CIRCUIT WITH COMPLETE FILTER

Storage of energy in choke $=\frac{LI^2}{2}$ in watt-seconds (Joules)

Dissipation of energy in load $=I^2R$ in watts

Where, L=henrys, I=amperes, R=ohms

For any given frequency with a single-phase rectifier, energy must be stored to carry the I^2R output for some portion of a half cycle. Doesn't it seem reasonable, since both the energy storage in the choke and the energy dissipation in the load are proportional to I^2, that there must be some relation between the values of L and R that will materially affect the circuit operation?

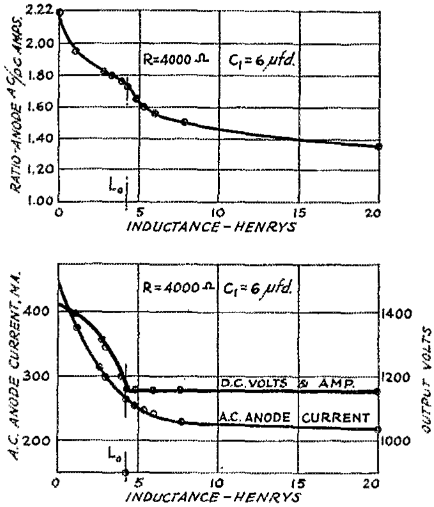

FIG. 3—CURRENT AND VOLTAGE RELATIONS AS FIRST CHOKE IS VARIED

In order to investigate this, five tests were

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[1] Pike and Maser, "A New Type of Rectifier Tube," *QST*, Feb., 1929; Maser and Saxton, "Mercury-Vapor Rectifier Ratings and Circuits," *QST*, March, 1931.—EDITOR.

made. In such investigations it is important to vary *only one independent element at a time.* Otherwise the results become obscure and the observations difficult to interpret. There are also critical conditions that must be avoided, in this case, particularly, resonance. With 60-cycle power the output of a full-wave single-phase rectifier has a fundamental frequency of 120 cycles. There may be some 60 cycles present if the tubes are unbalanced but usually it is negligible. Some values of inductance and capacity resonating at 120 cycles are given below. It is a good plan to memorize any pair of these values for better mental image. Resonant conditions will then be unconsciously avoided in carrying out rectifier tests.

TABLE I

Values of L and C resonating to 120 cycles

Resonance is given by the well known formula: $f = \frac{1}{2\pi\sqrt{LC}}$

Inductance Henrys	*Capacity Microfarads*
0.5	3.5
1.0	1.75
1.5	1.17
2.0	0.875
4.0	0.438
6.0	0.292
8.0	0.218
10.0	0.175
20.0	0.088

Note that a 6-henry choke would be far below resonance with a 1-μfd. condenser, a frequently used combination. But if the choke loses inductance due to d.c. saturation, a common occurrence, it might drop to 2 henrys or less, a not unheard of event, in which case resonance would be closely approached and disturbance of the filter circuit operation would be expected.

The test circuits are shown in Figs. 1 and 2. They are the usual type of rectifier circuit for this purpose and do not require detailed description. Fig. 1 was used for the first tests to eliminate complications of following filter sections. Fig. 2 was then used to prove that added filter sections did not affect the fundamental relations. Both a.c. and d.c. meters were used in the anode and rectifier output circuits. These meters read differently and the ratio of their readings is very significant of circuit operation and wave shape. A single meter was placed in the second anode circuit merely to check balance of the two rectifiers. The meters in the load circuit were d.c. only, since the smoothing was adequate to make the a.c. and d.c. readings substantially identical. In each test observations were made of all meter readings but only those giving significant data are reproduced herewith in the form of curves. The details of test procedure were as follows:

(Note: Table II.)

QUALIFICATIONS OF TEST OPERATION

Test No. 1 (Results shown in Fig. 3)

Readings were taken for successive values of L_1 and plotted as shown. The critical value of L_1 is indicated by a sudden rise in terminal voltage as the inductance is reduced. It is also indicated by the ratio of a.c. to d.c. anode current becoming about 1.75. This ratio is changing rapidly at this point.

Test No. 2 (Results shown in Fig. 4)

The main variable was the load resistance R. For each value of R the inductance L_1 was varied until the critical value was found, the critical point being determined as described under Test No. 1.

Test No. 3 (Results shown in Fig. 5)

The first condenser was varied alone, all other elements being held at fixed values.

Test No. 4. (Results shown in Fig. 6)

This duplicated the procedure followed in Test No. 2, the only difference being the added filter section as shown in Fig. 2.

Test No. 5 (Results shown in Fig. 7)

This duplicated the procedure followed in Test No. 3, except that filter section was added. The two condensers were varied simultaneously, C_1 always being twice C_2. This arrangement is a little different from common practice, but was followed advisedly from theoretical reasons which will not be elaborated here. It does not affect the conclusions as to critical inductance in any way.

THE CRITICAL AND OPTIMUM VALUES OF THE FIRST CHOKE

The tests show that there is a critical value of the first inductance. Fig. 3 shows that the anode direct current and the load voltage reach a constant value when the first choke is increased to its

TABLE II

Test procedure for determining the critical value of L_1

Test No.	*Variable Element*	*Other circuit elements*					*Object*
		L_1	L_2	C_1	C_2	*R Ohms*	
1. Fig. 1	L_1	Var.	0	6 μfd.	0	4000	To find critical value of L_1 for fixed circuit.
2. Fig. 1	R & L_1	Var.	0	6 μfd.	0	Var.	Crit. L_1 as affected by variations in load R.
3. Fig. 1	C_1	6.84H	0	Var.	0	4000	Crit. L_1 as affected by size of first condenser.
4. Fig. 2	L_1 & R	Var.	12H	4 μfd.	2 μfd.	4000	Crit. L_1 as affected by added filter section.
5. Fig. 2	C_1 & C_2	6.3H	12H	Var.	Var.	4000	Resonance effects with added filter section.

critical value. For larger values of inductance at L_1 the d.c. output remains constant. Although the anode direct current remains constant after the critical value of L_1 is reached, the a.c. value continues to decrease fairly rapidly until the first choke has twice the critical value, when further change occurs slowly. This value of twice the critical inductance may be called the "optimum inductance" and appears to be the value that should be used in filter design.

The value of critical inductance, which we will call L_0, is directly proportional to the load resistance — and nothing else (for a given frequency). This is shown by Fig. 4. The actual relationship is very simple:[2]

$$L_0 = \frac{R}{1000}$$

L_0 in henrys
R in ohms

The value of L_0 might also be affected by:

1. The values of filter condensers
2. Added filter sections
3. Rectified voltage
4. Frequency
5. Tube characteristics

The effect of condensers is shown in Figs. 5 and 7. As long as the condensers are large enough to avoid resonance, any increase in size has no effect on L_0. The circuit resonant point must be about one half or less of the impressed frequency, (one half or less of 120 cycles with full-wave single-phase 60-cycle rectifier). In the circuit of Fig. 1 the resonant point is the same as for a regular series resonant circuit and is given by the formula attached to Table I. When a filter circuit is added the system becomes a parallel resonant circuit coupled to the tube by the first choke and shunted by the load. In this case the resonant point becomes the cut-off frequency of the filter circuit.

The value of L_0 is independent of voltage. This is not shown in detail, but is implied by the checks at very low voltages mentioned in Footnote 2. The circuit of Fig. 1 was also tried out with transformer voltages from 960 to 2,720, the load voltages (d.c.) resulting from this input ranging from 435 to 1065. With a constant load of 2000 ohms this gave load currents running from about 200 to 550 ma. The critical value of inductance was the same in each case, being equal to R/1000 within 5%.

It was not possible to try out variable frequency. As the function of the choke is to supply energy between cycle peaks, the critical value should be inversely proportional to frequency. More intricate theoretical examination gives the same result, and any readers having 50 cycles, for example, should multiply values of L_0 from these test results by 6/5 to obtain the same operation.

Tube characteristics in general do not materially affect the value of L_0. So far it has been assumed that L_0 depends upon load resistance only. Strictly speaking, the total resistance in the circuit should be included, and this involves tube drop. Therefore if the rectifier tube resistance becomes an appreciable part of the whole circuit, it must be included in the value of R controlling the size of L_0. Where a tube has a definite starting voltage, seldom serious in commercial forms at present available, the critical value must be larger. There is no simple way of expressing this increase. Experiments with a rectifier tube where the starting voltage was about 20% of the (d.c.) load voltage increased L_0 by about 10%, so tube characteristics can in general be neglected within the limits of customary engineering error.

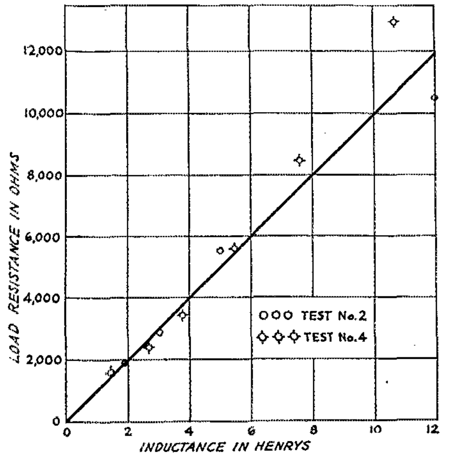

FIG. 4.— RELATION OF CRITICAL INDUCTANCE TO LOAD RESISTANCE

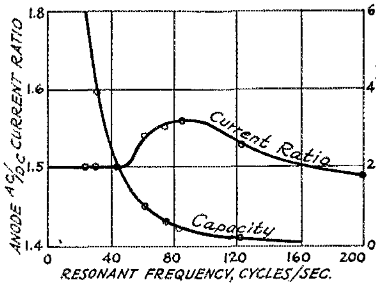

FIG. 5.—EFFECT OF RESONANCE ON ANODE CURRENT, INCOMPLETE FILTER

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[2] This same relationship holds for a wide diversity of rectifiers. It has been checked with a 12-volt 2-ampere copper-oxide rectifier, as well as an experimental tube type delivering 30 volts and 5 amperes. The same results were obtained with minor variations due to difference in tube characteristics.

EFFECT OF CRITICAL INDUCTANCE UPON CIRCUIT BEHAVIOR

The first choke, when properly chosen, not only reduces peak values of current, thus safeguarding the rectifier tube, but also improves several other operating features.

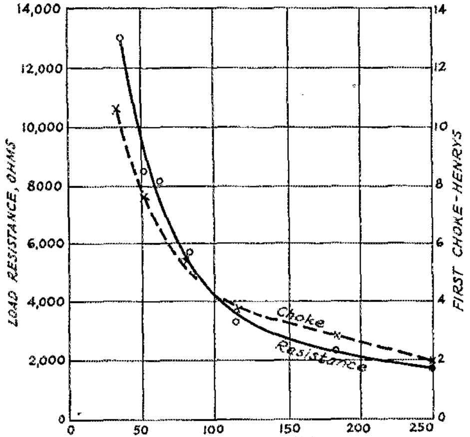

FIG. 6.—CRITICAL INDUCTANCE AS A FUNCTION OF LOAD RESISTANCE WITH COMPLETE FILTER CIRCUIT
See Fig. 4 for ratio of curves.

When the first choke equals the optimum value, the current wave through the anode of the rectifier is almost rectangular or flat-topped. Under these conditions the peak value of anode current is almost the same as the d.c. load current delivered (say 5 to 10% higher) and it is possible to run safely such a rectifier at a d.c. output current substantially equal to the peak current rating of the tube.

The voltage regulation of the rectifier is much improved.[3] When L_1 is less than L_0, light loads allow the output voltage to approach the peak value of the a.c. impressed voltage due to condenser storage. Heavier loads, meaning less load resistance, drag the voltage down to the average value of impressed a.c. If L_1 exceeds L_0 for all loads, the output voltage is always the average of the impressed a.c. (less resistance drops in the filter circuit) as shown in Fig. 3. The objection may be raised that this lowers the available d.c. voltage. As a matter of fact, it should be considered that the d.c. voltage *at full load* will be substantially the same as with other circuits and the improved regulation will prevent this voltage from rising to dangerous values at no load. There is also the additional point that more power can be drawn from the rectifier due to reduction of peak current to substantially the minimum possible.

The reduction of the alternating current in the anode circuit promotes economy in material. The power output of the rectifier is proportional to the anode direct current. The heating of the transformer secondary is proportional to the square of the alternating anode current. Thus by the use of a first choke of optimum inductance it is possible to reduce the size of the transformer secondary wire, or to make a hot transformer run cool.

A first choke of critical or optimum value will materially aid in ripple smoothing, provided resonant effects are avoided. This improvement in smoothing and reducing material in the transformer will compensate in cost for any increase in size of first choke.

DESIGN OF THE FIRST CHOKE

The rectifier circuit will operate between two load limits:

1. Full load output, minimum load resistance *R*.
2. No load output, load resistance=bleeder circuit.

At full load L_1 should be the optimum value of twice L_0 in order to reduce heating currents to a minimum. At no load L_1 should have a value of at least L_0 to prevent undue rise in voltage, impairing regulation and endangering the rectifier, condensers and associated equipment. For example:

Assume a rectifier to deliver about 300 milliamperes at 1000 volts.
The load resistance at full load is 3000 ohms.[4]
With 50 ma. bleeder current the no-load *R* is 20,000 ohms (approx.).
Optimum inductance at full load is 6 henrys.
Critical inductance at no load is 20 henrys.

A 20-henry constant inductance choke becomes rather large, but advantage can be taken of the tendency of iron-cored chokes to slide around in inductance with changes of d.c. and a smaller air gap can be used. It is, however, imperative that the choke be properly designed so that saturation does not pull the inductance down too far at full load.

Such a choke might be made approximately as follows:

Rating
7-henry 400-ma., storage 0.56 watt-seconds (to allow for bleeder current, etc.)
20-henry 50-ma., storage 0.025 watt-seconds

Core
Cross section: 1¾″ wide, laminations stacked 3″ thick; gross area 5.25 sq. in., net area 4.75 sq. in.
Window: 2½″ long by 2″ wide, area 4.5 sq. in.

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[3] c.f. Ed. Glaser, "Improving Voltage Regulation of Rectifier-Filter Systems," *QST*, October, 1931. Mr. Glaser has pointed out the desirability of varying inductance in the first choke. Measurements of L_1 in his circuit would make an interesting comparison with the definite values of L_0 found above.

[4] The effective load resistance is equal to the output voltage divided by the load current. — EDITOR.

Winding

- Coils: Two (2), one each leg, 2½" layer, 1" depth,
  - Core form, 1⅞ x 3⅛ ins.
  - Wire size, No. 24 B & S (400 milliamperes)
  - No. turns, 1500 each coil. 3000 total.
- Mounting: Assemble core in four legs.
  - Assemble coils on longer legs.
  - Mount with clamps and butt joints in core.
- Air Gap: Make two corners butt steel to steel.
  - Put spacers in other two corners.
  - Total thickness of all spacers .020 in.

Material

- Core steel should be 4% silicon transformer steel.
- If ordinary dynamo steel used, increase core area 20%.
- Space is figured for single-cotton-enamel covered wire.
- Use brass or wood core clamps. Do not use iron, because of high a.c. component in leakage field around gap.

Tests

The best way to test is to adjust gap at full load and no load conditions for best results. If tested on 110 volts 60 cycle a.c. the choke should draw 8 milliamps, showing an inductance under these conditions of 30 henrys.

Accuracy

The correctness of this design cannot be guaranteed since the actual inductance varies so much with type of steel, care in shearing and assembly, amount of a.c. component present and parts used in rest of circuit. It is generous in design and should prove satisfactory in the majority of cases. It will probably carry 500 ma. without overheating.

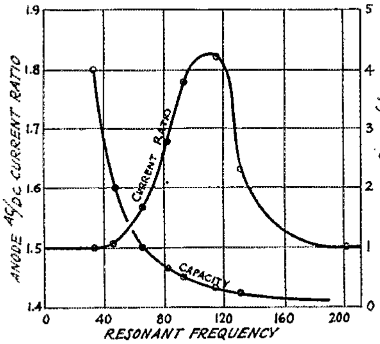

FIG. 7.—EFFECT OF RESONANCE ON ANODE CURRENT, COMPLETE FILTER

TESTING FOR BEST FIRST CHOKE

The simplest method of determining whether the first choke is properly limiting the peak value of current is to use an a.c. and a d.c. meter in series in the anode circuit. The ratio of a.c. to d.c. readings should be 1.75 at $L_1 = L_0$ and 1.5 when optimum L_1 is used. These same tests can be made with bridge-connected rectifiers. In this case the meters still must be put in the anode circuit of one tube and not in the transformer secondary lead.

In the meter test some precautions are required. The calibrations of the meters should be checked on d.c. and readings compared. They need not have absolute accuracy, but one should be corrected with respect to the other. Do not take reversed readings on the a.c. meter but leave it connected with the same polarity so that d.c. from the rectifier will flow through it in same direction as was used in calibration. This is important because some a.c. meters read slightly different for reversed d.c. Meters using rectifiers are not satisfactory for this purpose. The d.c. meter should be of the D'Arsonval type, such as Weston 301, and the a.c. meter should be of the dynamometer, iron-vane or thermocouple type, so that it reads true heating value (effective current).

SUMMARY

1. The first choke in a high voltage rectifier circuit has a critical value.
2. The henrys for critical value is load resistance divided by 1000.
3. The optimum value for full load operation is twice the critical value.
4. The critical value is independent of everything except load resistance (or, more accurately, total circuit resistance) and frequency.
5. Resonance with rectifier output frequency must be avoided.
6. A first choke of optimum value will:
   - A. Limit current peak to substantially a same value as d.c. output.
   - B. Improve smoothing of filter.
   - C. Greatly improve regulation of voltage.
   - D. Materially reduce heating of transformer secondary winding.
7. These optimum conditions can be tested for by means of the a.c. to d.c. current ratio in the tube anode circuit.
8. The inherent choke characteristics of varying inductance with direct current are advantageous to make critical inductance follow changes in load.
9. The size of choke required for optimum value is reasonable and approximates customary practice. However, it cannot be allowed to fall off too far, as load increases, due to saturation or poor design.

Strays

There's still another ham with the initials H.A.M. He is H. A. Morris (the same as W4KZ, curiously enough), W4LC, of Obion, Tenn. That makes three of them now, G6WY having started this business.