Distortion in Transformer Cores

Part IV.—REVISED DESIGN TECHNIQUE TO MINIMISE HARMONIC DISTORTION

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THE nature and extent of harmonic distortion in push-pull output transformers has been examined in detail in earlier instalments. This article, the last of the series, will be devoted to the consideration of ways and means of keeping this distortion under control.

IN designing a transformer for low distortion the first step is to select a "good" magnetic material for the core. In last week's instalment reasons were given for accepting Vicor (manufactured by Magnetic and Electrical Alloys, Ltd., of Wembley) as our starting point. An oscillogram showing the current distortion produced by this alloy at a flux density of 4,680 lines per sq. cm. was reproduced in Fig. 22, but to perform detailed calculations the distortion at all densities must be known. A series of current oscillograms at various flux densities is given in Fig. 24 and the graph obtained by analysing these wave forms is shown in Fig. 25. These two illustrations correspond to Fig. 3 and Fig. 5, which give the same information about Silcor 2. The final requirement is a curve connecting inductance with flux density. Such a curve is contained in Fig. 23, but for completeness it is reproduced here in Fig. 26.

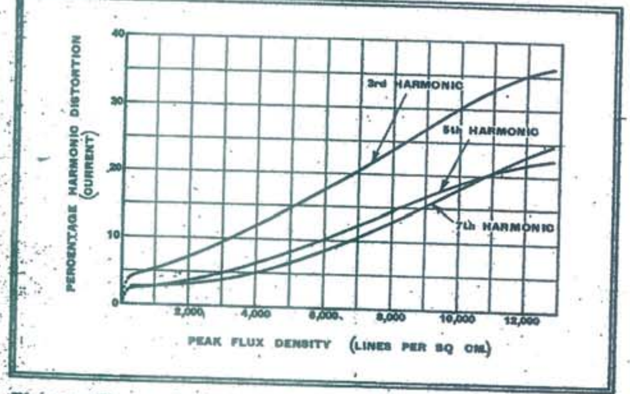

Fig. 25.—The graph obtained by plotting the result of an harmonic analysis of the wave forms of Fig. 24. The harmonics are expressed as a percentage of the fundamental.

Having fixed upon the core material, the second step is to consider how best it may be used. One could design a transformer in the conventional manner and claim an improvement by virtue of the better core. But there would still be one or two rather disconcerting criticisms. For one thing, the *intrinsic* distortion would be high. As can be seen from Fig.

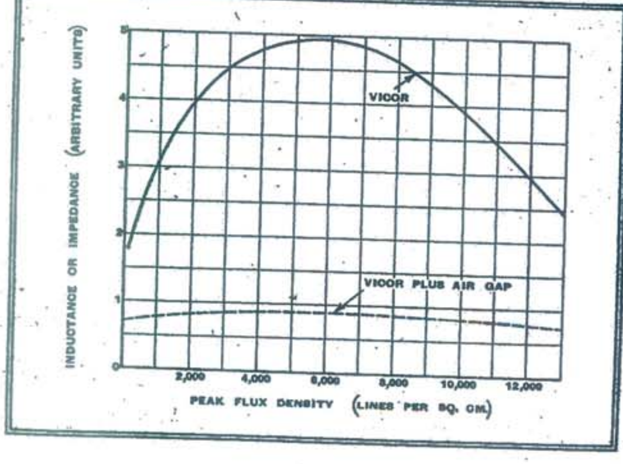

Fig. 26.—The full curve indicates the change of inductance (or impedance) with flux density in the case of a transformer having a closed magnetic circuit of Vicor. The dotted curve applies to a composite core of Vicor plus an air gap (see Table 7).

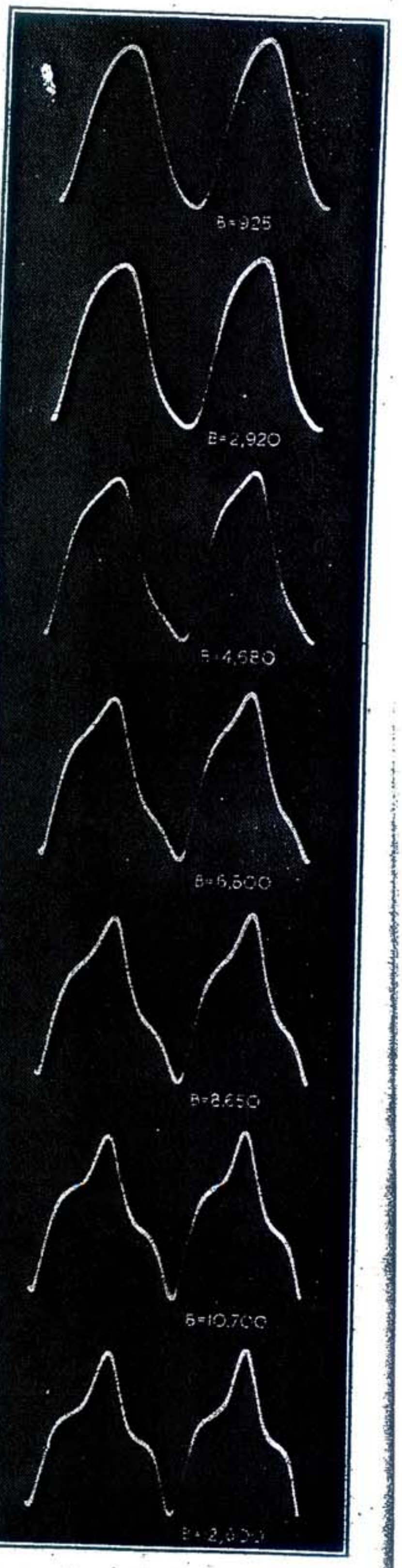

Fig. 24.—The oscillograms show how the current distortion varies with flux density in the case of Vicor. "B" is the value of the peak flux density in lines per sq. cm. The photographs should be compared with Fig. 3 (Part 1), which gave the same information about Silcor 2.

25, appreciable distortion occurs at quite low densities and it is only the somewhat fortuitous circuit conditions $\left(\frac{R}{Z_F}\right)$ that keep the working distortion within reasonable limits. It would be more satisfying if the transformer in itself could be made distortionless apart from the external circuit. Again, a small out-of-balance between the anode currents of the two push-pull valves will be sufficient to upset all the calculations. And there is still the little matter of frequency modulation which depends upon the external circuit for correction.

There is an extremely simple device whereby most of the troubles and worries mentioned above can be substantially lessened. That is by putting a suitable air gap in the magnetic circuit. Gaps have always been used for chokes and transformers carrying DC, but as far as the author is aware, such a technique has not been deliberately used by manufacturers to reduce intrinsic distortion apart from the question of polarisation.

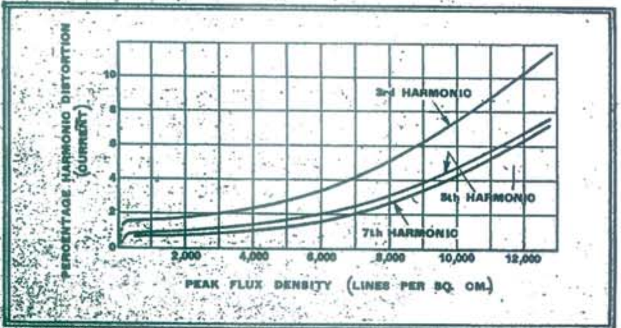

Fig. 27.—The intrinsic distortion of the core is materially reduced by an air gap. This graph should be compared with Fig. 25 which shows the distortion without a gap.

The effect of a gap can be easily understood with the aid of Fig. 26 and Table 7. Suppose a transformer, giving the relative inductances shown in the graph (Fig. 26) has a gap made in its core of a length such that the inductance at B=1,000 is reduced from 3 to, say, 0.73. These figures are, of course, purely relative, and the actual inductances may be anything, depending upon the core area and the number of turns on the primary. Since the impedance has been reduced, a greater magnetising current will flow. But the iron circuit still requires exactly the same current to magnetise it and to supply the various losses, from which it follows that the additional current must be that required to maintain the flux in the air gap. This additional current will be undistorted and will vary *directly* as the flux density.

Table 7 shows an approximate method of estimating the inductance and distortion curves for the composite core consisting of Vicor plus the air gap. Column 1 contains selected flux densities for which the relative magnetising currents taken by the Vicor are shown in column 2. These figures were obtained by testing the Vicor without a gap. The third column indicates the magnetising current required by the air gap, which is proportional to the flux density. The total current is tabulated in column 5, from which the new relative impedances can be deduced. It must be remembered that this method is only approximate because the magnetising currents for the Vicor and the air path are assumed to be in phase, and this is not strictly true.

The new impedance curve is drawn dotted in Fig. 26. The inductance has been greatly reduced by the gap but this is not necessarily important. The earlier examples have shown that any good output transformer has a far higher inductance than is strictly required for the preservation of the bass. Our new curve at least approximates to a straight line. In other words, instead of having an inductance that varies enormously with the signal voltage, we now have an inductance that remains sensibly constant. Another important advantage is that any normal out-of-balance between the anode currents will be far too small to have any effect upon the Vicor, which is protected in this respect by the gap.

Turning to the question of harmonic distortion, a change has occurred here, too. The curves in Fig. 25 give the distortion as a percentage of the fundamental. The air gap has increased the fundamental without altering the magnitude of the harmonic currents, and, therefore, these harmonics will be noticeably smaller when expressed as a percentage of the augmented fundamental. Columns 6, 7 and 8 show the revised distortion figures in the case of the particular gap chosen for the purpose of Table 7. These values have been plotted in Fig. 27.

Because the basic distortion (x) has been reduced to less than one-third of its original value it must not be assumed that

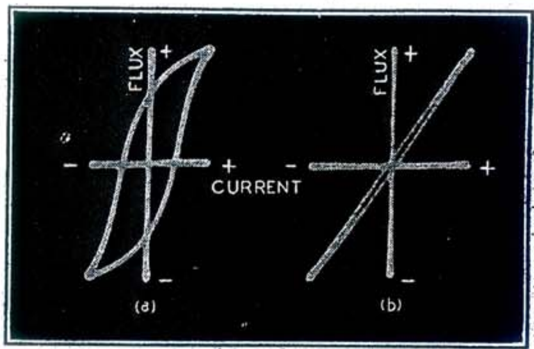

Fig. 28.—(a) shows the relationship between the instantaneous flux density and current in a closed core of Vicor. This approximates to the hysteresis loop. (b) gives the same information in the case of a gapped core. Note that the flux is almost proportional to the current.

a corresponding improvement will be found in the performance of the transformer. Actually, the working distortion has not been altered at all. Unfortunately, Z_F has been reduced just as much as x and the final result remains the same. But what we have done is to reduce the *intrinsic* distortion and make the performance of the transformer less dependent upon the external circuit. This modification is strongly reflected in the curve showing the relationship between the flux in the core and the magnetising current. Fig. 28 (a) shows this curve, which approximates to the hysteresis loop, for the ungapped transformer and Fig. 28 (b) repeats the curve for the gapped core. The latter is brought very close to the ideal, which would be a straight line.

The reader may be wondering why the gap chosen was one which reduced the inductance at B=1,000 in the ratio of 3 to 0.73. At first sight it looks as though a much larger gap would still further reduce the intrinsic distortion and make the transformer behave as though it were air cored. This reasoning is perfectly correct, but there are practical limitations to the possible magnitude of the gap. The larger the gap the lower the inductance, and hence more turns have to be wound upon the primary in order to keep the inductance up to the minimum allowable value. Increasing the turns means using finer wire

TABLE 7

Peak Flux Density	Vicor Magnetising Current	Air Gap Magnetising Current	Total Magnetising Current	Impedance of the Gapped Core	Distortion of Gapped Core (per cent.)		
					3rd Harmonic	5th Harmonic	7th Harmonic
263	4.2	7.8	12.0	71.0	—	—	—
537	7.0	15.8	22.8	75.7	—	—	—
925	10.5	27.4	37.9	79.0	1.5	0.8	0.6
2,920	22.0	86.3	108.3	87.0	1.84	0.95	0.71
4,680	33.2	138.0	171.0	88.0	2.65	1.50	1.17
6,800	48.2	201.0	249.0	88.0	3.87	2.37	1.94
8,650	69.8	255.0	325.0	86.0	5.62	3.50	3.10
10,700	107.0	317.0	424.0	82.0	8.15	5.10	4.95
12,000	168.0	373.0	541.0	75.0	11.2	7.4	6.9

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and obviously the wire gauge cannot be smaller than that which will safely carry the current. Also the DC resistance of the winding must not be permitted to reach too high a value.[1] Again, the leakage inductance must be kept within manageable proportions, and this limits the number of turns that can be employed.

With a view to showing the type of result that can be obtained with Vicor and the gap technique, a transformer was designed on a 1¼in. stack of No. 4 stampings to operate with two DA30 valves in Class A push-pull. The harmonic distortion given by this transformer at 50 c/s is indicated in Fig. 29. This should be compared with Fig. 12, which gives similar data relating to a well-designed transformer with a core of Silcor 2. Note that the Partridge Distortion Index[2] for the latter was 0.5 per cent., whereas the gapped Vicor reduces this figure to 0.2 per cent.

All the examples so far have employed the No. 4 stamping. The reason for this is that it is a very popular stamping and serves for the purpose of illustration as well as any other. But the No. 4 laminations are not necessarily the most suitable ones for audio-frequency transformer design. Greater iron section would be an advantage and so would be a slightly restricted window space. The former makes it possible to work at a lower flux density and the latter aids in the reduction of leakage inductance. The No. 56 stamping (Magnetic & Electrical Alloys, Ltd.) is a very good one. The dimensions of both the No. 4 and the No. 56 stampings are shown side by side in Fig. 30 for comparison.

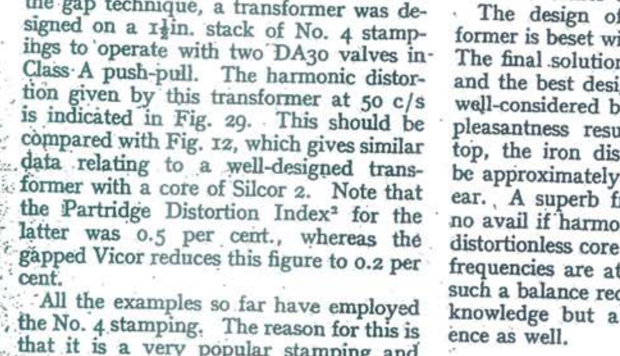

Fig. 29.—The distortion obtained under working conditions from an output transformer using a gapped Vicor-magnetic circuit. The Partridge Distortion Index is only 0.2 per cent., which is very low considering the size of the component.

If expense is no great objection, the size of the transformer can be increased and, theoretically, the iron distortion can be reduced to as low a value as one wishes. A large core section with ample window space will permit the winding of a primary with a very high inductance and a large air gap will be possible without jeopardising the bass response. The intrinsic distortion will, by this means, be made extremely low, and, no matter what the external circuit conditions, such a transformer would not produce harmonic distortion. But theory and practice do not collaborate harmoniously in this respect. The larger the transformer the more difficult it becomes to preserve the high-frequency response. Also, owing to the shape of the distortion curves in Fig. 5 and Fig. 25, it requires a very considerable reduction in the flux density to bring about any worth while improvement in the transformer distortion.

The design of a good output transformer is beset with conflicting desiderata. The final solution must be a compromise and the best design is that which gives a well-considered balance of evils. The unpleasantness resulting from the loss of top, the iron distortion, etc., should all be approximately equal as judged by the ear. A superb frequency response is of no avail if harmonic distortion is high; a distortionless core is wasted if all the high frequencies are attenuated. To achieve such a balance requires not only technical knowledge but a wide practical experience as well.

Conclusion

Looking back upon the information brought to light by these investigations, perhaps the most striking thing is the fact that the articles should have been written at all so late in the development of electro-acoustics. Amplifier technique has been subjected to the most rigorous analysis in the cause of fidelity, and has long since reached a very high standard. Speech transformers were used in communication work years before radio was invented and yet, apart from vague apprehensions, nobody seems to have seriously worried very much about the extent of the harmonic distortion they produce.

As far as so-called commercial reproduction goes, iron distortion is not very important. It occurs only at l o w frequencies, and if true bass is not catered for in the amplifier, then it can do no harm in the transformer. But the subject must be studied with the utmost seriousness by those seeking really high-quality reproduction. Distortion at low frequencies is more dangerous than perhaps the reader has, as yet, appreciated. The characteristics of the ear are such that the sensitivity increases very rapidly from the lowest audible notes up to around 500 or 600 c/s. The effect of this is that *2 per cent, seventh harmonic contained in a 50 c/s note can sound as loud as the fundamental itself.*

This statement is truly amazing, but a few figures will prove its validity. A distortion of 2 per cent. means that the voltage of the seventh harmonic (350 c/s) is 2 per cent. of that of the fundamental (50 c/s). In other words, the seventh harmonic is 34 db below the level of the

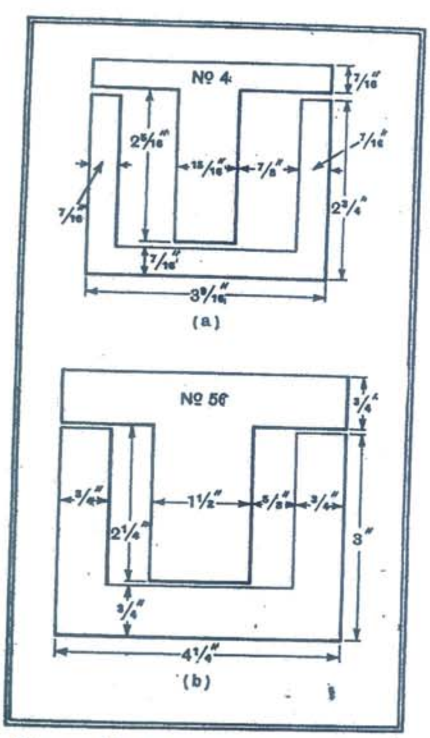

Fig. 30.—All the examples in this series have used the No. 4 stamping but this is not necessarily the best one. The No. 56 presents certain advantages mentioned in the text. The numbers are those of Messrs. Magnetic and Electrical Alloys, Ltd.

fundamental. But at a loudness level of 20 db the sensitivity of the ear increases by approximately 34 db between 50 c/s and 350 c/s. Hence the harmonic will sound to the ear as though it were 100 per cent.! One is, of course, assuming that the sensitivity of the loud speaker is the same at both frequencies. If it happens to be greater at 350 c.p.s., then the position is even worse.

Obviously, something must be done about iron distortion. A transformer response curve is only a snare and a delusion when examined alone. The response is important up to a point, but it *must* be considered in conjunction with the transformer harmonic distortion. To do this a simple and standardised method of expressing the distortion is required, and the Partridge Distortion Index is put forward as a tentative suggestion. It may be defined as the arithmetical sum (*not* RMS) of the percentages of the third, fifth, and seventh harmonics produced under working conditions at 50 c/s when the transformer is delivering its full rated output into a resistive load of value equal to the nominal secondary load. By substituting a resistance in series with the primary to take the place of the valve AC resistance, the test can be taken using the 50 c/s mains as the source of power. This scheme eliminates all possibility of valve distortion masking the transformer distortion, and avoids the risk of polarisation.

[1] See "Output Transformers—The Effect of Resistance," *Wireless World*, January 12th, 1939.
[2] See Part II, June 29th issue and also last paragraph of this article.