THE RESISTANCE OFFERED BY IRON WIRES TO
ALTERNATING CURRENTS.

BY ERNEST MERRITT.

THE abnormally large resistance offered by iron wires to alternating currents has been a matter of common observation for many years. The increased resistance is due to what is known as the "throttling effect," which prevents an alternating current from penetrating completely to the center of the wire ; the effect is especially noticeable in iron because of the high permeability. The results of this throttling effect in the case of iron wires are sometimes quite startling, as for example in the case cited by Lord Kelvin, where the accidental short-circuiting of an alternating circuit by an iron bar caused the outer surface of the bar to be heated almost to redness, while the inner portions were scarcely warmed.

In the case of the non-magnetic metals, for which the permeability is constant, the computation of the resistance offered to alternating currents of a given frequency is a matter of no great difficulty. But in the case of iron the permeability changes with the current strength in accordance with a law that is as yet unknown. By assuming what appears to be a reasonable average value for μ and substituting this in the formula derived on the assumption of μ constant, we can obtain an approximate value for the resistance offered by an iron wire under given conditions ; but, as I have pointed out in a previous article,¹ we have no means of telling how close this approximation will be. In fact it is questionable whether a formula derived upon the assumption of a constant permeability can be correct even in its general form ; for it is to be remembered that the value of μ will not only change during the course of an alternation, but will also be different at a given instant in different parts of the wire, since the iron will be magnetized to a different extent at the surface from what it is at the center. The whole question is so

¹The Distribution of Alternating Currents in Cylindrical Wires, *PHYSICAL REVIEW*, Vol. 5, p. 47.

complicated that an experimental study of the subject seems necessary before correct conclusions can be reached.

The experiments described below were carried out at my suggestion by Mr. H. H. Denio,¹ to whose care and patience the consistent results are due. The method employed is open to criticism for several reasons, so that no high degree of accuracy can be claimed for the numerical values obtained. Nevertheless I think that the results will serve a useful purpose in calling attention to the more important peculiarities in the behavior of iron wires, and that they may be of assistance in planning a more accurate study of the phenomena.

The iron wire whose resistance was to be measured was made one arm of a Wheatstone Bridge, the other arm being formed by large wires of German silver. The wires were not coiled, but stretched between two heavy brass blocks, *AB* and *CD* (Fig. 1), these being mounted on a long board.

The distance between *A* and *C* was 220 cm. The resistance of the German silver wire *BD* was about 0.5 ohm.

Fig. 1.

Current, either alternating or direct as desired, entered the bridge at *AB* and *CD* and divided between the two branches in the ordinary way. The balance of the bridge was determined by means of a telephone, *T*, one of whose terminals was permanently connected to one end of the iron wire *MC*, while the other could be moved along *BD* until the sound in the telephone reached a minimum. Complete silence was never obtained.

It was at first thought that the failure to obtain silence in the telephone was due to the fact that the inductance of *AC* was greater than that of *BD*. Several attempts were made to remove the difficulty by increasing the self induction of *BD*, but without success. I am now of the opinion that the trouble was caused by the variations occurring in the self induction of the iron wire during the course of an alternation. If this is true the difficulty is one that is inherent in the method.

¹ Thesis for the degree of B. S., 1898. Cornell University Library.

Although complete silence could not be obtained, it was always possible to set to a minimum of sound in the telephone with considerable certainty. A change in the quality of the sound in passing through the minimum often assisted in locating N .

The alternating current used had a frequency of about 130 periods per second.

It was expected that the resistance offered to alternating currents would depend upon the current strength. The current flowing in the iron wire was therefore varied through a wide range of values, the resistance being measured for each. Curves were then plotted showing the relation between current and resistance for each wire tested. The resistance for direct current was determined by the same apparatus. Since the current used was often strong enough to appreciably heat the wire, the measurements made with direct currents were also repeated with a number of different current strengths. The ratio of the alternating current resistance to the direct current resistance for the same current strength is then a

Fig. 2.

measure of the throttling effect. It will be observed that this method of procedure eliminates the errors that might arise from changes in resistance due to the heating of the wire.

Seven different wires were tested, ranging in diameter from 0.032 cm. to 0.476 cm. The curves shown in Fig. 2, which refer to a wire of 0.114 cm. in diameter, are typical of the behavior observed in all cases. The lower curve (D) shows the variation in

resistance with current strength as determined by using a direct current in the bridge. The increase in resistance in this case is due to the wire becoming heated. Curve *A* shows the resistance offered to alternating currents, also plotted as a function of the current strength. In Fig. 3 a similar set of curves is shown for a wire 0.366 cm. in diameter. With small current it was difficult to measure the resistance with accuracy, so that the portion of the curves near the origin are less reliable than those corresponding to larger currents.

In their general character the results represented by these curves are what might be anticipated from the known magnetic properties

Fig. 3.

of iron. For small currents the iron is only weakly magnetized, so that its permeability is small. For such currents the behavior of the iron is therefore not very different from that of the non-magnetic metals, whose resistance, for the frequency and sizes of wire used, should be practically the same for alternating currents as for direct currents. As the current in the wire is increased the resulting magnetization becomes greater, and for a time the permeability rapidly increases. During the range of current values for which μ is large the throttling effect is well marked, the alternating current resistance being appreciably larger. The increase in resistance is of course greater for large wires than for small ones. If the current is increased still further, the outer layers of the wire begin to satu-

rate, and the permeability of this part of the iron is in consequence diminished. Roughly speaking, the wire is now equivalent to a core of high permeability, which is surrounded by a shell of practically non-magnetic material. The thickness of this saturated or non-magnetic layer increases with increasing current until finally the wire is saturated throughout, after which it again behaves like a non-magnetic substance and the resistance for alternating currents becomes appreciably the same as that for direct currents. The current for which the alternating current resistance is a maximum, as well as the relative value of this maximum resistance, will evidently depend upon the size and magnetic qualities of the wire.

A glance at the curves plotted in Figs. 2 and 3 shows that the results obtained by Mr. Denio are qualitatively the same as the above considerations would lead us to expect. Any quantitative test of these conclusions must of necessity be very incomplete. It is gratifying to observe, however, that the measured values of the alternating current resistance do not differ greatly from those resulting from an approximate theoretical treatment. In the case of the smaller wire, whose diameter was 0.114 cm., an alternating current of 3.5 ampères, corresponding to a maximum of about 5 ampères, would give $H = 18$ as the maximum magnetizing force at the surface. The average permeability of soft iron when carried through a cycle having this maximum magnetizing force is not far from 1000.¹ For the interior of the wire the value of H would be less than 18 and permeability would therefore be somewhat larger. If we put the average permeability of the wire equal to 1600, the specific resistance being about 10,000, the ratio of the alternating current resistance to the ordinary resistance of the wire should be about 1.15. The observed value of this ratio, as shown by the curves in Fig. 2, was 1.34. The discrepancy between these two values, although considerable, is probably not greater than should be expected, for the computed value depends on the assumption of a *constant* permeability. For a current of 3.5 ampères the outer layers of the wire are already approaching saturation. For still larger currents the permeability would therefore be less than 1600, and we should expect the alternating current resistance to diminish with increasing

¹ Ewing, Magnetic Induction in Iron and other Metals, p. 107.

current. That this conclusion is verified by experiment is shown by the curve in Fig. 2.

A similar computation in the case of the larger wire (diameter = 0.366 cm.) shows that for a current of 7 ampères the alternating current resistance should exceed that for direct currents in the ratio of about 2.8 to 1. The value of this ratio determined by experiment was 3.2. But for a current of 7 ampères the magnetic force at the surface is only slightly greater than unity, so that saturation is not yet reached. The rapid decrease in resistance shown in Fig. 3 for larger currents is therefore hard to explain.

A number of other wires were tested, the results being in general more satisfactory with the wires of larger diameter. While the cases cited above are typical, it must be admitted that in some instances the quantitative agreement between observed and predicted results was even less satisfactory than in the case mentioned. Further experiments with more reliable methods will doubtless indicate more clearly in what way the approximate theory must be modified in order to become applicable to the magnetic metals.