July 23, 1935. E. KARPLUS ET AL 2,009,013

ALTERNATING CURRENT APPARATUS

Filed June 1, 1934 4 Sheets-Sheet 1

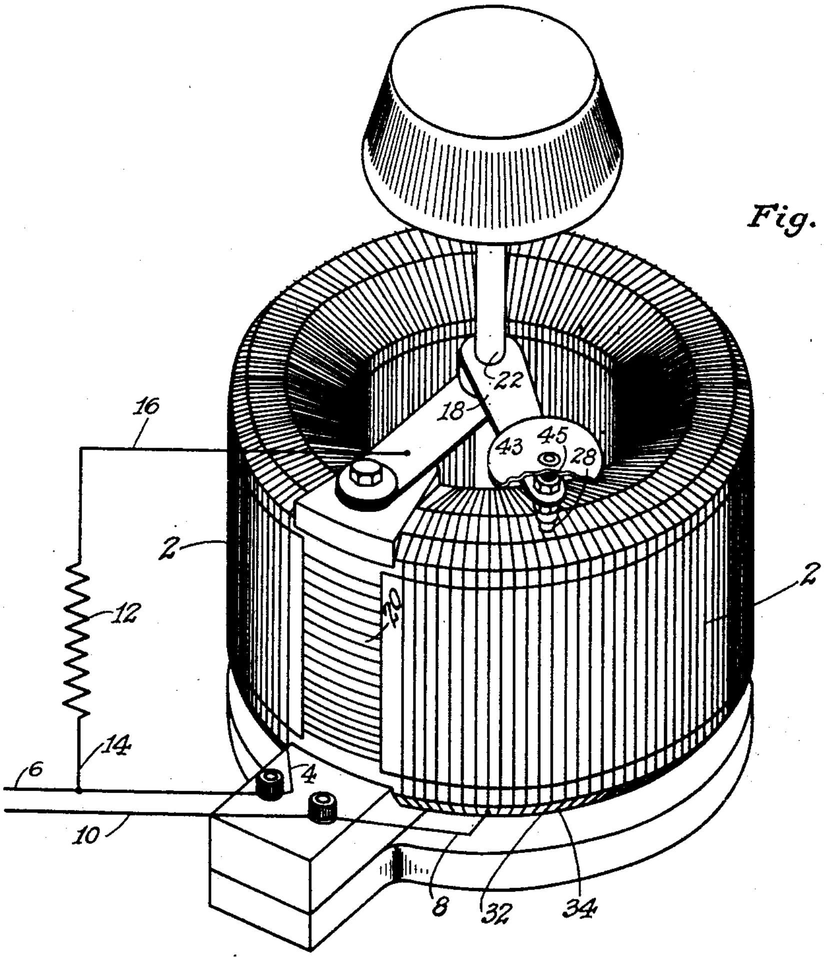

Fig. 1.

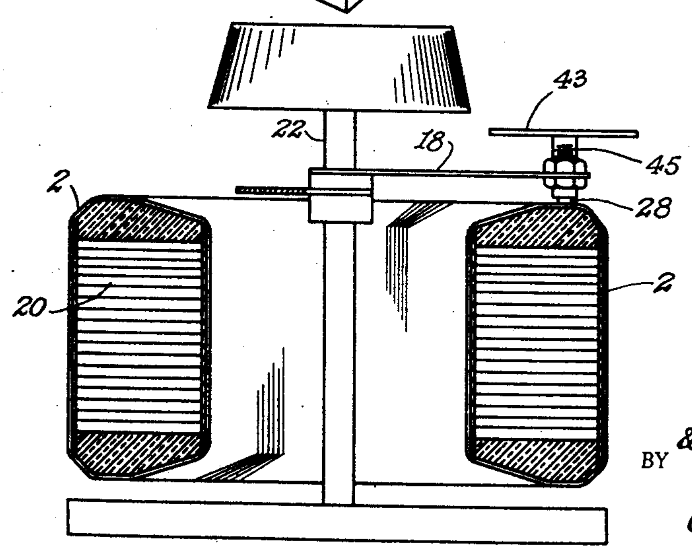

Fig. 2.

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ALTERNATING CURRENT APPARATUS

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Fig. 3.

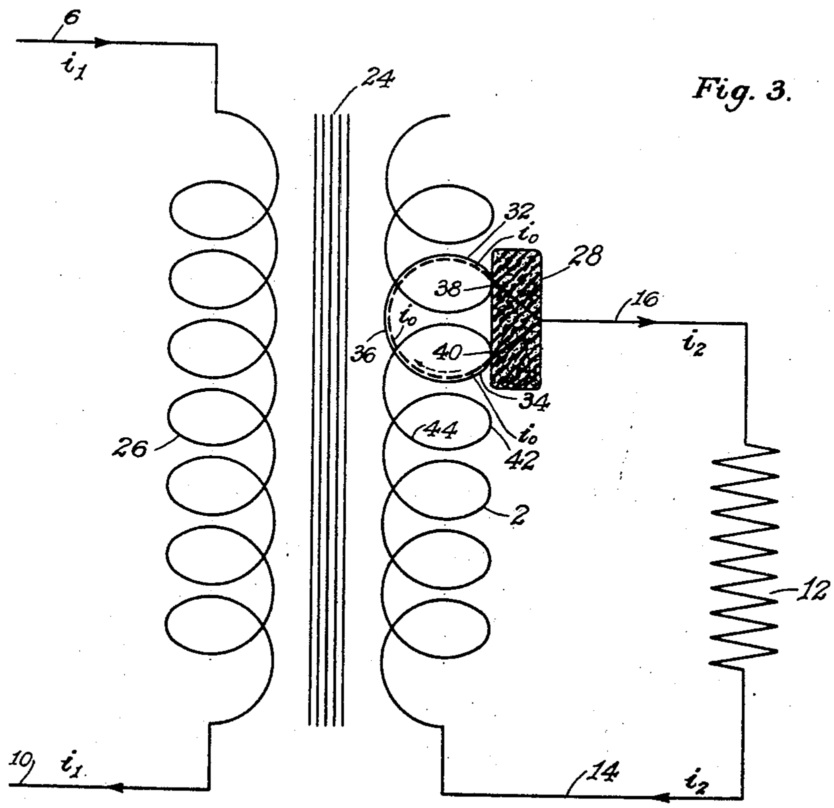
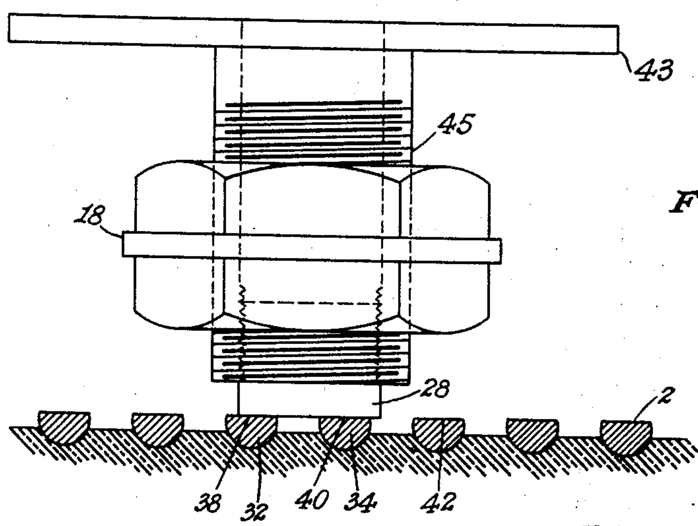


Fig. 4.



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ALTERNATING CURRENT APPARATUS

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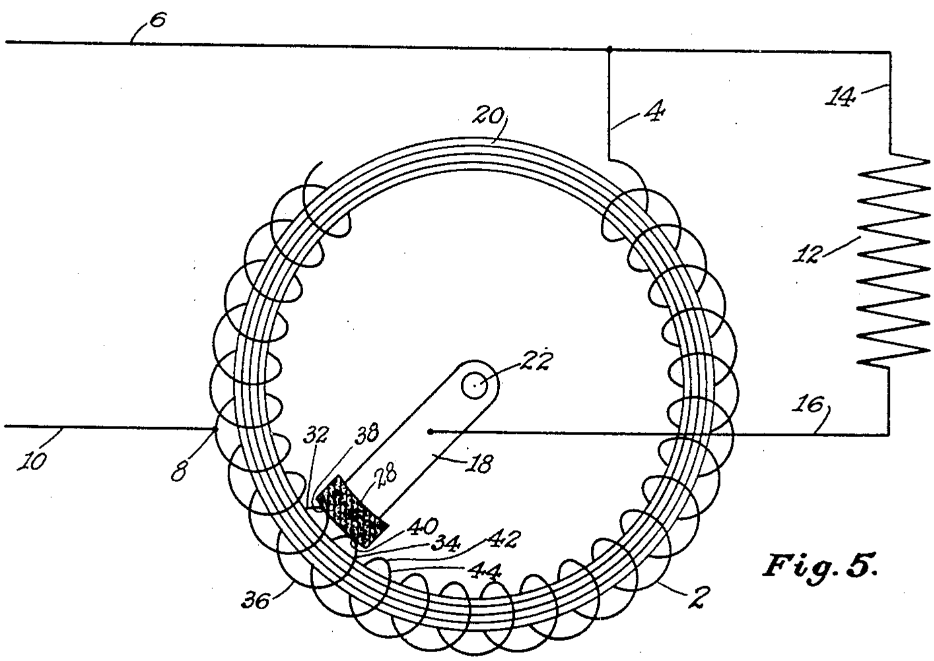

Fig. 5.

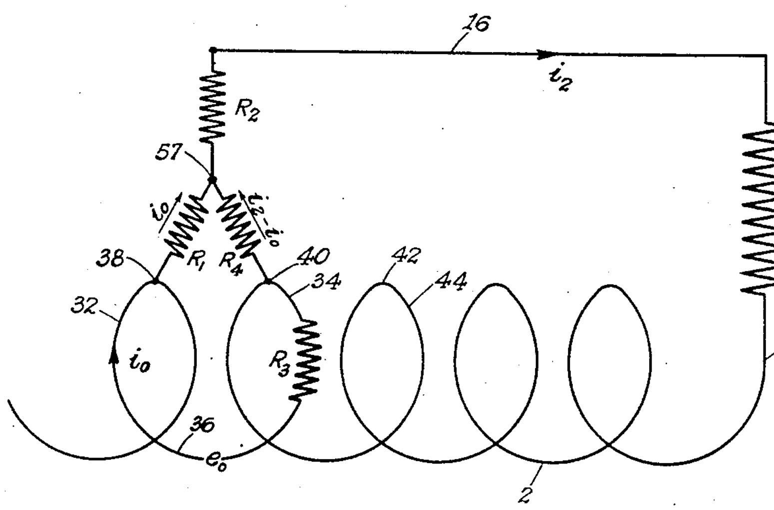

Fig. 6.

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ALTERNATING CURRENT APPARATUS

Filed June 1, 1934 4 Sheets-Sheet 4

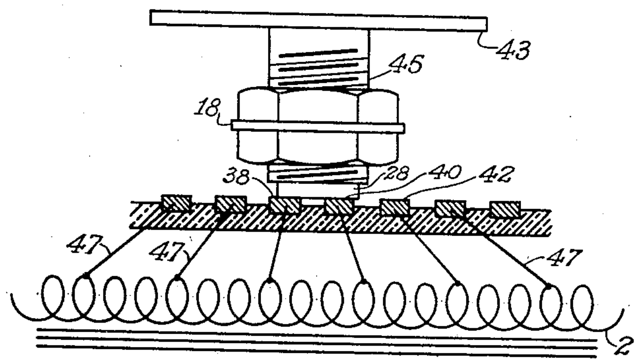

Fig. 7.

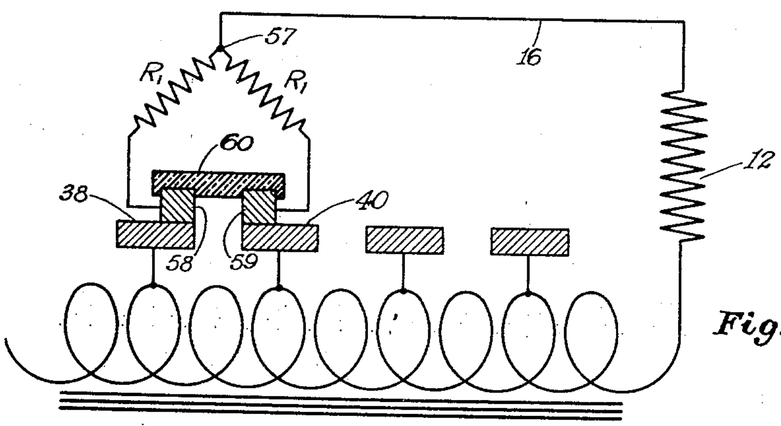

Fig. 8.

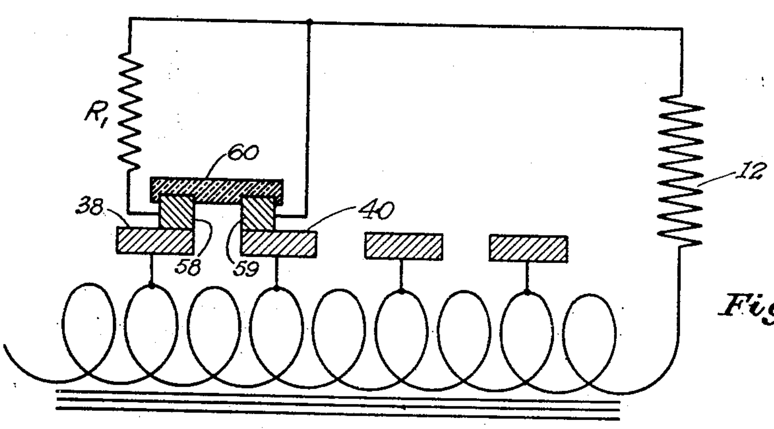

Fig. 9.

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Patented July 23, 1935

2,009,013

UNITED STATES PATENT OFFICE

2,009,013

ALTERNATING-CURRENT APPARATUS

Eduard Karplus and William Norris Tuttle, Cambridge, Mass., assignors to General Radio Company, Cambridge, Mass., a corporation of Massachusetts

Application June 1, 1934, Serial No. 728,470

6 Claims. (Cl. 171—119)

The present invention relates principally to alternating-current apparatus, such as transformers and choke coils, and particularly to apparatus of this kind in which a movable contact means, such as a contact member, is employed to vary either the voltage or the usable portion of a winding. The invention also relates to arrangements for making successive connections to a series of points at different electrical potentials without interrupting the circuit.

It has heretofore been proposed to provide apparatus of the above-described character, in which no resistance is introduced in the contact member. Such apparatus is either wholly inoperative or, if operative at all, can work only with a low-voltage winding; and then only at low efficiency. Otherwise, there would be liability of excessive short-circuit current, resulting in damage to the transformer.

In the copending application, Serial No. 673,447, filed May 29, 1933 by Eduard Karplus, a very simply constructed transformer or choke is described in which these difficulties are overcome. A resistive contact member makes successive connection with points of the winding, and is always in connection with at least one point, and, in certain positions, short-circuits adjacent points. The contact member is given a resistance sufficiently high to substantially reduce the short-circuit current, and sufficiently low so that excessive heating does not result from the flow of the useful current. Highly efficient operation is thus possible, even when the contact member moves over a high-voltage winding, because of the resistive nature of the contact member, whereby the current caused by connecting two adjacent turns together is limited, preventing over-heating.

One of the objects of the present invention is to provide an improved transformer or choke of the class described in the said application in which the heating of the contact member is reduced and the useful output increased.

Another object is to provide a contact means for making connection successively with points at different potential without interrupting the circuit, in which the energy loss in the contact means is considerably reduced.

Another object of the invention is to provide new and improved alternating-current apparatus of the above-described character that shall be simple in construction, efficient in operation and cheap to manufacture. Other and further objects will be explained hereinafter, and will be particularly pointed out in the appended claims.

The invention will be more fully described in connection with the accompanying drawings, in which Fig. 1 is a perspective of a toroidal auto-transformer constructed according to one embodiment of the present invention; Fig. 2 is a longitudinal section of the same through the axis of the toroid; Fig. 3 is a diagrammatic view of a circuit arrangement of a modification in which separate primary and secondary windings are employed; Fig. 4 is an enlarged view of a brush, making contact on the winding; Fig. 5 shows the circuit arrangement of the device of Fig. 1; Fig. 6 is a diagram of a circuit equivalent electrically to the secondary circuit of Fig. 3, and Figs. 7, 8 and 9 show modified contact arrangements in which contact studs are employed in place of the turns of the winding.

Referring, first, to Figs. 1, 2 and 5, an auto-transformer winding **2** is connected, at an end terminal **4** and at a tapped terminal **8**, respectively, to line conductors **6** and **10**, between which the line voltage is applied. A load **12** is connected by a conductor **14** with the line conductor **6** and by a conductor **16** with a movable contact member **18**. The auto-transformer winding **2** is wound, preferably in toroidal form, about a circular or cylindrical, iron core **20**, at the axis of which is disposed a shaft **22**. The contact member **18** is fixed to the shaft **22** and carries a brush contact **28** that engages successive turns of the winding **2**. To adjust the voltage applied by the auto-transformer **2** upon the load **12**, it is merely necessary pivotally to move the contact member **18** and its shaft **22** about the axis of the toroid.

In the auto-transformer of Figs. 1, 2 and 5, the conductors **6** and **10** constitute the primary connections, and the conductors **14** and **16** the secondary connections of the winding **2**. The principles of the operation are, however, the same, if the winding **2** is the secondary winding of an ordinary-type transformer, as illustrated in Fig. 3, having an iron core **24** and a primary winding **26** connected with the line conductors **6** and **10**. It will, of course, be understood that the toroidal form may be used in connection with the transformer of Fig. 3, and the straight form of Fig. 3 may be used with the auto-transformer of Fig. 1. Where the straight form of winding 2 is used, the brush 28 is naturally slidable instead of, as in Figs. 1 and 4, rotatable. The load 12 is shown in Fig. 3 connected by the conductor 14 to a terminal of the secondary winding 2 and by the conductor 16 to the brush contactor 28.

According to a feature of the present invention, the voltage of the winding 2 is rendered continuously adjustable in a novel manner. This may be understood more particularly from the enlarged diagrammatic showing of Fig. 3, where the primary current is indicated at i_1, and the conductors 14 and 16 are assumed to carry a load current i_2. The brush contactor 28 is wider than the distance between the intermediately disposed contact points 38 and 40 of two adjacent turns 32 and 34 of the winding 2. The brush 28 will, therefore, always engage at least one turn of the winding 2. As the brush 28 slides or pivots over the winding 2, furthermore, it will happen that, every so often, it will short-circuit at least one complete turn 36, between the points 38 and 40. The short circuit is indicated in Fig. 3 by dotted lines, and is assumed to have a current i_0 and a voltage e_0. Assuming the brush 28 to be moved downward, as viewed in Fig. 3, for example, as soon as, or before, the brush 28 leaves the point 38, it will make contact with a corresponding point 42 of the next turn. Upon leaving the point 38, the brush 28 will, of course, break the short circuit of the turn 36, but it will at the same time, or before, effect the short circuiting of the next-lower-adjacent turn 44. One such turn 36 or 44, therefore, is always short-circuited by the brush 28 and the load current i_2 is thus at no time interrupted as the voltage is changed during the movement of the brush 28 from one point or turn to another.

With the arrangement shown in Fig. 8, the maximum width of the contact means is less than the distance between the inside edges of alternate contact points, so that more than one turn is never short-circuited, and part of the time no turn is short-circuited, although contact is always maintained with at least one point. This result can be obtained from the arrangement of Figs. 3, 4, 5 and 7 by slightly decreasing the width of the brush. The narrower brush results in less heating of the contact member, but may reduce somewhat the smoothness of control.

The short-circuit current depends on the voltage between adjacent contact points and on the resistance of the short-circuited turn 36 and of the brush 28. The brush or contact means must have a high enough resistance to prevent damage due to the short-circuit current, and low-enough resistance not to cause excessive heating due to the flow of the useful current, as pointed out in the said application. The heating of the brush, however, can be materially reduced, and the useful output increased, if the brush is given a particular value of resistance which depends only on the voltage between adjacent contact points, and on the current exchanged with the external circuit. The following analysis determines the optimum value of brush resistance.

In Fig. 3, the brush 28 is shown making simultaneous contact with points 38 and 40 of the winding 2, and with the conductor 16. The brush is therefore seen to be a three-terminal resistance. Now it is well known in electrical theory that any three-terminal resistance is equivalent, from the standpoint of the circuits of which it forms a part, to three independent resistances connecting the three terminals to a common point. In Fig. 6, therefore, the brush of Fig. 3 has been replaced by three resistances, R_1, R_2 and R_4.

Fig. 6 is drawn for the case in which the movable contact is symmetrically located with respect to the contact points 38 and 40. The equivalent resistances R_1 and R_4, from the contact points 38 and 40 to the common point 57 would, therefore, be equal if the same current were flowing in each. It is well known, however, that the resistance between a copper contact and a brush of carbon composition, for example, may vary considerably with the current flowing through it. It is therefore necessary to consider the general case, as shown, in which the two resistances R_1 and R_4 may have different values. Each of the resistances R_1 and R_4 includes not only the internal resistance of the contact member, but also the resistance across the contact. R_1 is thus the total resistance, from the interior of the wire of the turn 36, at the point 38 or 40, through the contact and material of the contact member, to the equivalent junction point 57.

Proceeding with the analysis, in Fig. 6, the resistance of the short-circuited turn is indicated by R_3. If this resistance is large enough, it will aid in reducing the short-circuit current, but it has been found, in practice, that the resistance of the winding cannot be made large enough to aid materially in this respect without at the same time lowering too greatly the efficiency of the transformer. This is due to the fact that each turn must have the same resistance R_3 in order for the brush to operate satisfactorily in all positions. The resistance of only one turn operates to reduce the short-circuit current. The resistances of all the turns cooperate to lower the efficiency of the transformer.

As an illustration, it has been found, in the case of an auto-transformer, that the resistance of the turn may not be greater than 20 per cent of the required brush resistance without causing more than a 10 per cent reduction in the transformer efficiency. In the case of a transformer with separate primary and secondary, the resistance limit is 5 per cent for the same reduction in efficiency. In neither case is the allowable resistance of the turn great enough to affect appreciably the design of the brush.

In Fig. 6, the resistance R_2 represents that part of the brush resistance which can be considered confined to the external circuit. In practical cases, this resistance can be made small in comparison with the resistances R_1 and R_4. In Fig. 4, for example, the metal sleeve 45 surrounding the resistive brush 28 extends close to the contact surfaces 38 and 40 and very much reduces the equivalent resistance R_2 included in the external circuit. The equivalent resistances R_1 R_4, in this case, result principally from the resistances of the contact surfaces and of those portions of the brush immediately adjoining them. In the remainder of the analysis and in the claims to follow, we shall assume that the resistance R_2 is negligible and shall use the term "brush resistance" to mean the equivalent resistance R_1 or R_4, as above defined.

It is desired to determine a value for the brush resistance such that, for a given value of current delivered to the external circuit, and for a given value of e_0, the total energy loss in the two brush resistances R_1 and R_4 will be a minimum. The short-circuit current i_0 flows in one of these resistances, and the difference between the load current and the short-circuit current flows in the other, as indicated in Fig. 6. The total energy loss in the two resistances is, therefore, given by

$$W=R_1i_0^2+R_4(i_2-i_0)^2 \qquad (1)$$

Equating to zero the voltages around the short-circuited turn 36, the further relation is obtained:

$$e_0=R_1i_0-R_4(i_2-i_0) \qquad (2)$$

whence it follows that:

$$i_0=\frac{e_0+R_4i_2}{R_1+R_4}. \qquad (3)$$

Substituting (3) in (1), and simplifying,

$$W=\frac{e_0^2}{R_1+R_4}+i_2^2\left(\frac{R_1R_4}{R_1+R_4}\right). \qquad (4)$$

Equation (4) is a perfectly general expression for the total heat generated in the two equivalent resistances R_1 and R_4. As indicated earlier, W must be computed using the values of R_1 and R_4 corresponding to their respective currents.

The first term is seen to be the dissipation due to the voltage between adjacent contacts acting across the two brush resistances in series. The second term is due to the load current flowing through the two brush resistances in parallel. In cases where these resistances do not vary with the current, the two components are independent, and the first term is the total, no-load, brush dissipation.

It is desirable to introduce, as parameter, the square root of the ratio of the two brush resistances such that

$$R_4=n^2R_1. \qquad (5)$$

A substitution of (5) in (4) yields:

$$W=\frac{e_0^2}{(l+n^2)R_1}+i_2^2R_1\frac{n^2}{(l+n^2)} \qquad (6)$$

To determine the value of R_1 which, for a given resistance ratio n^2 will result in minimum loss, the derivative of W with respect to R_1 in (6) is set equal to zero, giving:

$$\frac{e_0^2}{R_1^2}=i_2^2n^2. \qquad (7)$$

Substituting (5) in (7) and taking the square root of both sides,

$$\sqrt{R_1R_4}=e_0/i_2=R_0. \qquad (8)$$

Equation (8) is to the effect that, if the two brush resistances are in fixed ratio, the minimum loss is obtained when their geometric mean is equal to the voltage between adjacent contact points, divided by the load current. As indicated in (8), this ratio will be designated by R_0, which may be called the optimum brush resistance. If the two brush resistances are equal, each should have the value R_0 for minimum total loss. If they are unequal, their geometric mean should have this value.

For design purposes, it is important to know how much the brush resistances may deviate from the best values without resulting in excessive dissipation. It is noted from (5) that

$$R_1=\frac{l}{n}\sqrt{R_1R_4} \qquad (9)$$

$$R_4=n\sqrt{R_1R_4} \qquad (10)$$

The ratio of the geometric mean of the brush resistances to the optimum brush resistance may be introduced as a second parameter, as follows:

$$k=\frac{i_2}{e_o}\sqrt{R_1R_4} \qquad (11)$$

It follows, therefore, from (9) and (10), that

$$R_1=ke_o/ni_2 \qquad (12)$$

$$R=nke_o/i_2 \qquad (13)$$

Substituting (12) in (6), and simplifying,

$$W=e_oi_2\left(\frac{l+k^2}{2k}\right)\left(\frac{2n}{l+n^2}\right) \qquad (14)$$

In (14), the product e_oi_2 is the total brush dissipation when the two brush resistances are equal, and equal to the optimum value. This quantity may be denoted by

$$W_o=e_oi_2. \qquad (15)$$

The factor in the first parenthesis gives the increase in loss which results from employing a geometric-mean brush resistance different from the optimum value given by (8). The second factor represents the decrease in total loss which can be obtained with unequal brush resistances.

It should be noted that the two functions in parenthesis are reciprocals of one another. Further, each is a function which has the same value, whether the variable or its reciprocal is substituted. In other words, $k=10$ gives the same increase in dissipation as $k=0.1$, etc. For reference, some values of the function $(l+x^2)/2x$, which may be either factor, according to whether x represents k or n, may be tabulated, as follows:

x	$(l+x^2)/2x$
1.	1.00
1.5	1.08
2.	1.25
2.5	1.45
3.	1.67
5.	2.60
10.	5.05
20.	10.0
50.	25.0

From the table, it is seen that, if the geometric-mean brush resistance is raised to twice the optimum value, the loss is increased 25 per cent. To reduce the loss to its previous value by means of the second factor in (14), however, one brush resistance would have to be four times the other, since n^2, and not n, is the ratio of the brush resistances.

In the case of the brush symmetrically located between the two contact points 38 and 40, the two brush resistances may be unequal, and n may have a value different from unity, only as a result of variation of the contact resistance with the current flowing.

The two factors in (14) tend to offset one another, and consequently (8) must be rather closely satisfied in order to obtain less loss than given by (15), by means of unequal contact resistances.

Even under these conditions, appreciable reduction of heating takes place only if relatively large ratios of resistance can be obtained. If

$n^2=2$, for example, only a 6 per cent reduction in heating can take place.

Fortunately, a much simpler condition exists which may readily be satisfied in practice. If either brush resistance has the value,

$$R=e_0/i_2 \qquad (16)$$

substitution in (4) shows that the total loss is then independent of the other resistance and equal to the value given by (15), that is, to the product of the voltage between adjacent contacts, multiplied by the load current. This very much simplifies the problem, for in satisfying (16), one brush resistance alone may be considered, without regard to the other. As shown above, the simpler condition given by (16) results in only slightly greater heating than is obtainable under practical conditions by satisfying the more difficult requirement (6).

If (16) is substituted for R_1 in (3), the expression reduces to

$$i_0=i_2 \qquad (17)$$

and under this condition, therefore, (i_2-i_0), the current through the contact 40, is equal to zero and the entire energy loss takes place in the resistance to the higher potential contact 38. If this latter resistance has the value given by (16), the resistance to the lower potential point 40 is of no importance in determining the total brush dissipation of the fully loaded transformer. At lower values of load current, although current then flows through both contacts, Equation 4 shows that the total heat loss in the brush is always less than at full load. As indicated earlier, therefore, the only concern is with the brush resistance when the full-load current is flowing through it, and relation (16) should be satisfied under this condition.

It should be pointed out further that, in view of (16) and (17),

$$R_1i_0=R_1i_2=e_0 \qquad (18)$$

which shows that the voltage drop due to the load current flowing through the resistance R_1 from the point 38 is equal and opposite to the turn voltage e_0. This furnishes a convenient and practical test for determining whether or not the brush resistance satisfies requirement (16). In making the test, the brush is moved from the position shown in Fig. 6 until contact is made with only one point of the winding. The load resistance 12 is then adjusted until the desired current i_2 is flowing, the voltage drop between the turn 36 and the conductor 16 is measured with a voltmeter, and the measured voltage is compared with e_0, the known voltage per turn. Although, in this test, contact is made nearer the center of the brush than when a turn is short-circuited, it has been found that the brush resistance is not altered by any considerable amount.

In studies of carbon brushes, it has been pointed out by some authorities that the contact resistance between a carbon brush and a metallic surface tends to vary with current in such a way that the potential drop remains substantially constant. This is particularly true at large current densities. The more familiar concept of a variable resistance is employed in the present analysis, however, it being realized that the two treatments express the same phenomena in different terms.

The power dissipated in the brush at no load is another readily measurable quantity, but is useful only in cases where the brush resistance does not vary with the current. This quantity can be observed with a wattmeter by comparing, at no-load, the power input to the transformer, when the brush touches only one point, to that taken when a turn is short-circuited. Since the two resistances are equal under this condition, substitution of (16) in (4) gives

$$W=e_0^2/2R=\tfrac{1}{2}e_0i_2 \qquad (19)$$

and the brush dissipation at no load is seen to be one-half of the loss at full load. It should be noted further that the short-circuit current under the same conditions at no load is given by

$$i_0^1=e_0/2R_1=\tfrac{1}{2}i_2 \qquad (20)$$

again using Equation 16. This is likewise seen to be half of the full-load value and holds also only for a constant-resistance brush.

It has already been pointed out that, in cases where the brush dissipation must be made as low as possible, the dimensions of the brush are made small enough so that never more than one contact interval is short-circuited at one time. In the case of small transformers, where the required heat may more readily be dissipated, it is desirable, since fine wire is employed, to arrange the brush to make simultaneous contact with several adjacent turns. This provides very smooth control and reduces considerably the wear on the winding. As mentioned earlier, the arrangements shown in Figs. 3, 4, 5 and 7 alternately short circuit two turns and one turn.

The analysis which has been given may readily be applied to contact members which short-circuit several turns simultaneously. The total potential difference short-circuited should be used in the formulae in place of the voltage between adjacent contacts. In some cases, such as where a brush of circular cross-section is employed, the outside turns touching the brush make contact with such small area that the contact resistance is abnormally high. In such cases, the outside turns contribute little to the total loss, and the effective number of turns short-circuited is one or two less than the nominal total. In such cases, therefore, the brush resistance should be equal to the effectively short-circuited voltage divided by the load current.

For example, in the case of a small auto-transformer of 1-ampere rating employing a hollow, cylindrical core 2⅞ inches outside diameter, 1⅛ inches inside diameter and 1⅜ inches high, 560 turns of No. 28 A. W. G. wire are employed for 115 volts, 60 cycles. The wire is spaced about 14 mils between centers, and a round carbon brush ⅛ inch in diameter is employed. Consequently, the brush extends across eight turns and effectively short-circuits perhaps six turns. The optimum brush resistance, being proportional to the short-circuited voltage, is therefore six times the value given by (16), and the minimum total loss, under this condition, is six times that obtained from Equation 15. Using the above data, the optimum brush resistance is computed to be 1.2 ohms and the minimum loss 1.2 watts.

This amount of heat can be dissipated without employing radiating fins. It would probably not be practicable to employ a brush narrow enough to short-circuit fewer than three turns in a transformer of this size, and probably no more than two watts could be dissipated without fins, which are undesirable in a small compact instrument. If only three turns are short-circuited and the dissipation is allowed to be two watts, then the value of k may not be greater than 6.35, i. e., the brush may not have less than 1/6.35 or more than 6.35 times the ideal resistance computed as specified above. The ideal value is 0.62 ohm and the limits are therefore 0.098 ohm and 3.72 ohms for a brush which short-circuits three turns. If the brush short-circuits six turns, as actually constructed, the corresponding limit of k is 3.0, the optimum brush resistance 1.24 ohms, and the resistance limits 0.41 ohm and 3.72 ohms.

In the case of a similar, larger auto-transformer of 5-amperes rating, the outside diameter of the core is 4 inches, the inside diameter 2⅛ inches, and the height 2½ inches. 300 turns of No. 20 A. W. G. wire are used for 115 volts, 60 cycles. The diameter of the brush is ⅛ inch, and since the distance between turns is about 32 mils, three or four turns are always covered by the brush. Only two turns are effectively short-circuited, however, and twice the voltage per turn should therefore be employed in designing the brush and computing the loss. In this case, the optimum brush resistance is 0.15 ohm and the minimum loss 3.8 watts. A radiating fin is employed on the brush and perhaps 6 watts could be dissipated. The maximum allowable value of k is therefore computed from expression (14), assuming $n=1$ or that the brush resistances are equal, to be 2.8. The resistance limits are therefore 0.053 and 0.42 ohm.

In a still larger similar unit of 15-ampere rating, the core has an outside diameter of 5½ inches, an inside diameter 2½ inches and a height of 2½ inches. 160 turns of No. 14 A. W. G. wire are employed for 115 volts, 60 cycles. Two brushes are used, and are narrow enough so that more than one turn is never short-circuited at one time. In this case, the optimum brush resistance is 0.05 ohm and the minimum loss 10.8 watts. The brushes pass through a metal, heat-radiating disc the diameter of which is as large as the core. Elaborate means would be required to radiate much more heat. Perhaps 16 watts is the practical limit. The maximum permissible value of k is therefore computed, as before, to be 2.6.

It is to be observed, therefore, that, with three transformers, as constructed, satisfactory operation can not be obtained if the brush resistance is more than three times or less than one-third of the voltage between adjacent points, or the total voltage effectively short-circuited, where several turns are covered by the brush, divided by the maximum current delivered to the load. It has been seen, however, that in the case of the 1-ampere transformer, the use of a narrower brush might raise the tolerance factor to 6 or 7. If this 9 to 1 range of resistance variation be substituted in (6), the ratio of no-load brush dissipation to full-load dissipation will be found to vary between 0.1 and 0.9.

With all the transformers described, the current which can be delivered to the load is limited by the copper loss in the winding. That is, for each transformer, there is a maximum value of load current above which damage to the transformer will result due to heating of the winding. As indicated earlier, the brush should be designed so that the condition (16) for minimum brush dissipation is satisfied when this maximum current is flowing to the load.

The procedure in measuring the brush resistance has been described for cases where never more than one turn is short-circuited. In the more complicated cases, a brush can be tested independently of the associated transformer by setting it on a series of turns similar to those of the winding but not connected to one another. The brush pressure should be approximately the same as with the transformer. Current equal to the maximum safe current for the transformer can then be caused to flow from one of the turns into the contact and the corresponding potential difference between the external-circuit connection of the contact and the turn measured with a voltmeter. The brush resistance is then equal to the measured potential difference divided by the current through the contact. This procedure is satisfactory when as many as four turns are covered by the brush. If from five to ten turns are covered, the measurement should be made similarly, except that the current should be caused to flow simultaneously from two adjacent turns at the same potential, the total current into the contact member being the maximum safe current for the transformer, as before. Both in this case and in the case where the current enters the contact from only one turn, the test should be repeated several times, employing different turns to conduct the current; to make certain that a representative average result is obtained. Although the conditions outlined for these tests are not those of actual operation, the approximation is sufficiently close for practical purposes. Where the term "brush resistance" or "resistance of the contact means" is employed hereafter, or in the appended claims, therefore, the particular resistance determined by the above procedure is referred to.

The toroidal construction shown in the preferred embodiment of the present invention is advantageous in facilitating making contact with every turn of a winding. If the rectangular form is used, a simple slider can operate on only one leg, and even a double slider can utilize only two of the four legs.

The use of a slider operating directly on the turns of the winding provides a simple and inexpensive means of obtaining the low voltage between adjacent contact points which is necessary to secure efficient operation.

Finally, even with low voltage per turn, the resistive contact member is required in order, in practical cases, to reduce sufficiently the heat resulting from the short-circuited turns.

The simultaneous use of all three of these features makes a particularly useful and efficient device which can be constructed for operation at wide ranges of voltage and current. For example, in the case of the above-mentioned transformers, previously proposed, even when a toroidal form was used, the resistance of the metallic contact member was so low that it was necessary to restrict operation to very low voltages. In other cases, where taps were brought out, economic considerations prevented the use of sufficient taps, so that the resistances introduced could make the device operable in all positions of the movable contact means.

The novel design of a moving contact which has been disclosed can obviously be applied with advantage in many types of apparatus other than the transformer or choke coil which has been described. In any case where it is desired to make connection successively with points of different potential without interrupting the circuit, the contact of the present invention is applicable, and Equation 11 gives immediately the value of brush resistance which should be employed. The voltage e_0 is the voltage between adjacent contact points, just as in the case of the transformer described. Such applications are considered to fall within the scope of the invention.

The relationships which have been developed are equally applicable whether or not the resistances are introduced into the circuit by means of the single resistive contact piece 28, or by any other method. For example, in Fig. 7, the movable contact 28 may be made of low-resistance material, and resistances introduced into each of the connections 47, as has been done heretofore. Greatly improved operation of the device results, however, if each of these resistances has the value given by Equation 16 in accordance with the present invention.

There are other arrangements which are obviously equivalent electrically to the contact system of Fig. 6. Instead of employing two points of the same resistive contact member 28 to touch the points 38 and 40, as in Fig. 4, separate low-resistance contacts may be employed and the required resistances R_1 connected between them externally, as shown in Fig. 8.

Following Equation 17, however, it has been shown that, when the transformer is loaded, the resistance to the point 40 is of no importance in limiting the short-circuit current, and can consequently be reduced to zero, resulting in the arrangement shown in Fig. 9.

The two movable contacts 58 and 59 in Figs. 8 and 9 are arranged to move simultaneously at fixed separation, as by being attached to the single, movable, insulating piece 60, or by any other method. Also, any other arrangement of contacts may be employed which results in the same sequence of connections when the control member is moved. These connections are as follows: in one position of the control, the movable contacts make connection respectively with adjacent points of the winding. As the control is advanced from this position to the left in Figs. 8 and 9 in the direction of higher potential, the contact 59 leaves the lower-potential point 40 and for an appreciable space makes no connection. Next, the movable contact 59 makes connection with the higher-potential point 38 and for an appreciable space thereafter both movable contacts are connected to the same point. Contact 58 then leaves point 38, making no connection, and then subsequently makes connection with the next higher point, while the contact 59 is still in connection with point 38. The relative positions are now as at first, but advanced one contact. The cycle then repeats.

In the particular arrangement shown in Figs. 8 and 9, certain dimensional relationships are necessary if the connections are to be made as described. It is evident that the width of each of the movable contacts 58 and 59 must be less than the spacing between the inside edges of adjacent stationary contacts. Also the distance between the inside edges of the movable contacts must be less than the width of one of the stationary contacts. Further, the distance between the outside edges of the movable contacts must be less than the distance between the inside edges of any pair of alternate fixed contacts to prevent the bridging of two potential intervals.

In the arrangement of Fig. 9, the single resistor R_1 should be given the value determined by Equation 16, just as if two resistors, or a resistive brush making two contacts, were employed. It is evident, therefore, that both the no-load short-circuit current and the no-load brush dissipation are twice as great as the values given in the analysis for the other cases. The arrangement is quite satisfactory, however, because at full load the dissipation is the same as for the cases analyzed.

The resistive brush of Figs. 1, 2, 3, 4, 5 and 7 may be made of a mixture of carbon, graphite and powdered copper in proportions to give the required specific resistance, or the required potential drop.

Means should be provided to conduct and radiate away the heat produced in the contact brush 28. The heat radiator is shown in Figs. 1 and 2 as a large metal disk 43 on the stem 45 that carries the brush contactor 28. In Fig. 5, too, the arm 18, of metal, is shown made very wide to radiate the heat. Other heat radiators may be employed.

The uses of the present invention are very numerous—almost as numerous, in fact, as alternating-current problems themselves. The novel transformer of the present invention may be used in connection with 60-cycle or other power lines and wherever continuous variation of voltage combined with high efficiency is desirable, but it is by no means limited to power lines and can be applied at audio or higher frequencies, as well. It may be employed not merely with a constant, but also with a fluctuating line voltage from which it is desired to obtain therefrom a constant voltage. A toroidal construction such as is illustrated in Figs. 1, 2 and 5, the contact arm 18 of which is rotatable about the axis of the shaft 22, is particularly advantageous. As an illustration of one practical application of the invention, the new variable-ratio transformer is cheaper and more efficient than the dissipating power rheostats and the elaborate thyratron controls employed at the present day for dimming theatre lights. The transformer of the present invention will not fail, like thyratrons do. As a further illustration, the invention is readily adapted also for the smooth starting and highly efficient speed control of electric machines, such as induction motors. The invention may be used for testing and calibrating voltages and currents of varying magnitudes and is adapted for use with large or small currents or voltages.

The invention is not, furthermore, limited to use with one-phase circuits, as two or three or any other number of brushes 28 may be operated simultaneously. The toroidal type of variable-ratio transformer illustrated in Fig. 1 is particularly adapted for use where more than one variable transformer is needed.

Further modifications will be obvious to persons skilled in the art. It is therefore desired that the appended claims be broadly construed except insofar as limitations may be necessary to be imposed in view of the prior art.

What is claimed is:

1. Electrical apparatus of the character described provided with a winding adapted to be connected with an external circuit, the winding being designed to exchange current with the circuit at values not greater than a predetermined safe value above which the winding would become damaged by such exchange of current, the winding having a plurality of points, a contact member for making contact with the winding, means for connecting a point of the winding and the contact member to the external circuit,

and means for actuating the contact member to cause the contact member to engage the points successively, the width of the contact member being greater than the distance between two successive points, whereby the contact member will always maintain engagement with at least one point until the contact member engages the next point, thereby in certain positions to produce a short-circuit between adjacent points and prevent interruption of the current in the external circuit into the contact member, the value of the resistance of the contact member being such that when the contact member makes simultaneous contact with two adjacent points, at the time of the exchange of said predetermined, safe current between the winding and the external circuit, the geometric mean of the resistances of the contact to said adjacent points is not less than about one-third and not greater than about three times the voltage between said adjacent points divided by said predetermined, safe current.

2. Electrical apparatus of the character described provided with a winding adapted to be connected with an external circuit, the winding being designed to exchange current with the circuit at values not greater than a predetermined safe value above which the winding would become damaged by such exchange of current, the winding having a plurality of points, a contact member for making contact with the winding, means for connecting a point of the winding and the contact member to the external circuit, and means for actuating the contact member to cause the contact member to engage the points successively, the width of the contact member being greater than the distance between two successive points, whereby the contact member will always maintain engagement with at least one point until the contact member engages the next point, thereby to produce a short-circuit between adjacent points and prevent interruption of the current in the external circuit into the contact member, the value of the resistance of the contact member being such that when the contact member makes simultaneous contact with two adjacent points, at the time of the exchange of said predetermined, safe current between the winding and the external circuit, the difference of potential between the higher potential point and the external circuit is not less than about one-third and not greater than about three times the voltage between said adjacent points.

3. Electrical apparatus of the character described provided with a winding adapted to be connected with an external circuit, the winding being designed to exchange current with the circuit at values not greater than a predetermined safe value above which the winding would become damaged by such exchange of current, the winding having a plurality of points, a contact member for making contact with the winding, means for connecting a point of the winding and the contact member to the external circuit, and means for actuating the contact member to cause the contact member to engage the points successively, the width of the contact member being greater than the distance between two successive points, whereby the contact member will always maintain engagement with at least one point until the contact member engages the next point, thereby in certain positions to produce a short-circuit between adjacent points and prevent interruption of the current in the external circuit into the contact member, the resistance of the contact member being of the order of the voltage between adjacent points divided by the said predetermined, safe current.

4. Electrical apparatus of the character described provided with a winding adapted to be connected with an external circuit with which the winding is adapted to exchange current, the winding having a plurality of points, a contact member for making contact with the winding, means for connecting a point of the winding and the contact member to the external circuit, and means for actuating the contact member to cause the contact member to engage the points successively, the width of the contact member being greater than the distance between two successive points, whereby the contact member will always maintain engagement with at least one point until the contact member engages the next point, thereby in certain positions to produce a short circuit between adjacent points and prevent interruption of the current in the external circuit into the contact member, the resistance of the contact member being sufficiently large so that the power dissipated due to the short-circuit current at no load is not less than about one-tenth and not greater than about nine-tenths of the power dissipated in the contact member at full load and sufficiently small not to reduce appreciably the current flowing through the contact member to the external circuit.

5. Electrical apparatus of the character described provided with a winding having a plurality of turns and adapted to be connected with an external circuit, the winding being designed to exchange current with the circuit at values not greater than a predetermined, safe value above which the winding would become damaged by such exchange of current, a contact member for making contact with the winding, means for connecting a point of the winding and the contact member to the external circuit, and means for actuating the contact member to cause the contact member to engage the turns successively, the width of the contact member being greater than the distance between two successive turns, whereby the contact member will always short-circuit at least one turn and thereby prevent interruption of the current in the external circuit into the contact member, the resistance of the contact member when said predetermined current is exchanged with the external circuit being greater than about one-third and less than about three times the voltage effectively short-circuited by the contact member divided by said predetermined, safe current.

6. Electrical apparatus of the character described provided with a substantially toroidal winding having a plurality of turns and adapted to be connected with an external circuit, the winding being of diameter not substantially greater than about four inches and of height not substantially greater than about two-and-one-half inches and being designed to exchange current with the circuit at values not greater than a predetermined, safe value at which the winding would become damaged by such exchange of current, a contact member rotatable about the axis of the toroid for making contact with the winding, means connecting a point of the winding and the contact member to the external circuit, and means for rotatably actuating the contact member to cause the contact member to engage the turns successively, the width of the contact member being greater than the distance between two successive turns, whereby the contact member will always short-circuit at least

one turn and thereby prevent interruption of the current in the external circuit into the contact member, the resistance of the contact member when said predetermined, safe current is exchanged with the external circuit being greater than about one-seventh and less than about seven times the voltage effectively short-circuited by the contact member divided by said predetermined, safe current.

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