Aug. 18, 1959 R. W. TRIPP 2,900,612

VARIABLE COUPLING TRANSFORMERS

Filed Sept. 26, 1955 2 Sheets-Sheet 1

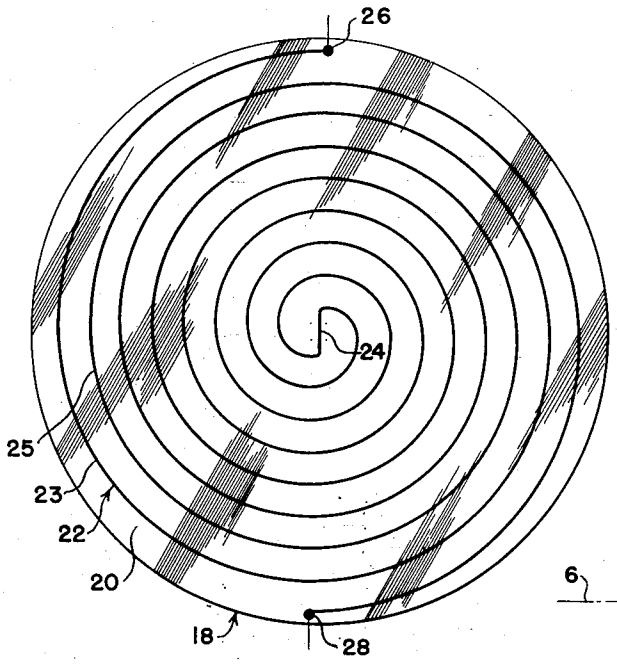


FIG. 1

FIG. 5

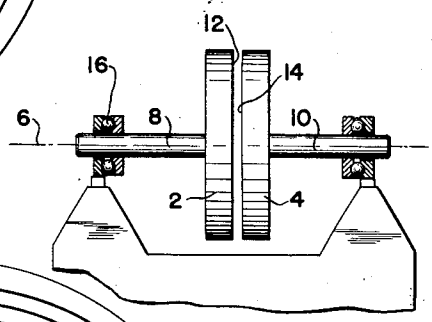
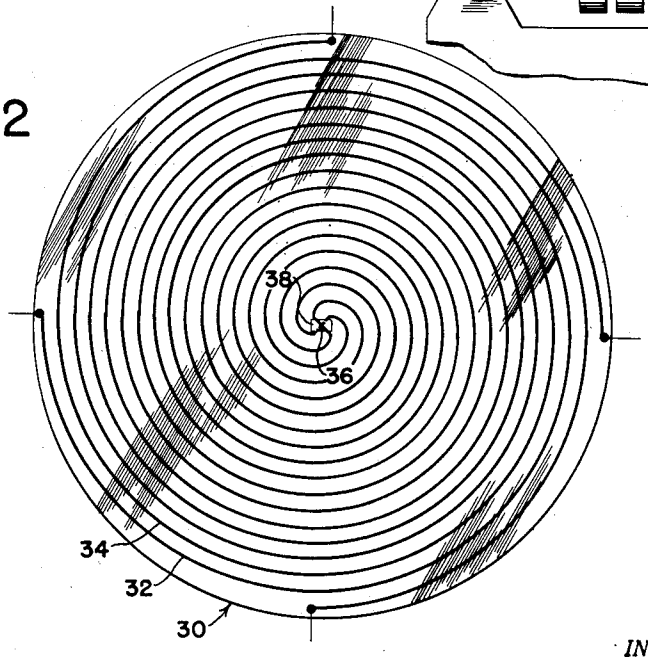


FIG. 2



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FIG. 3

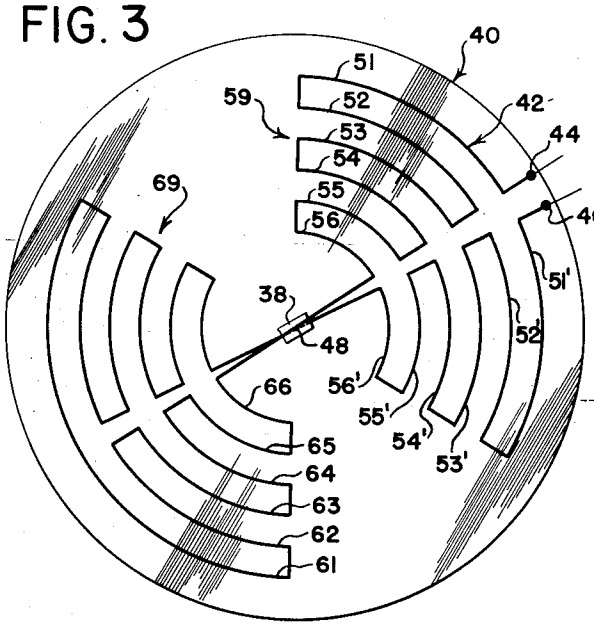


FIG. 6

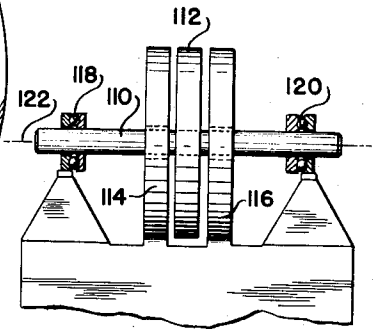
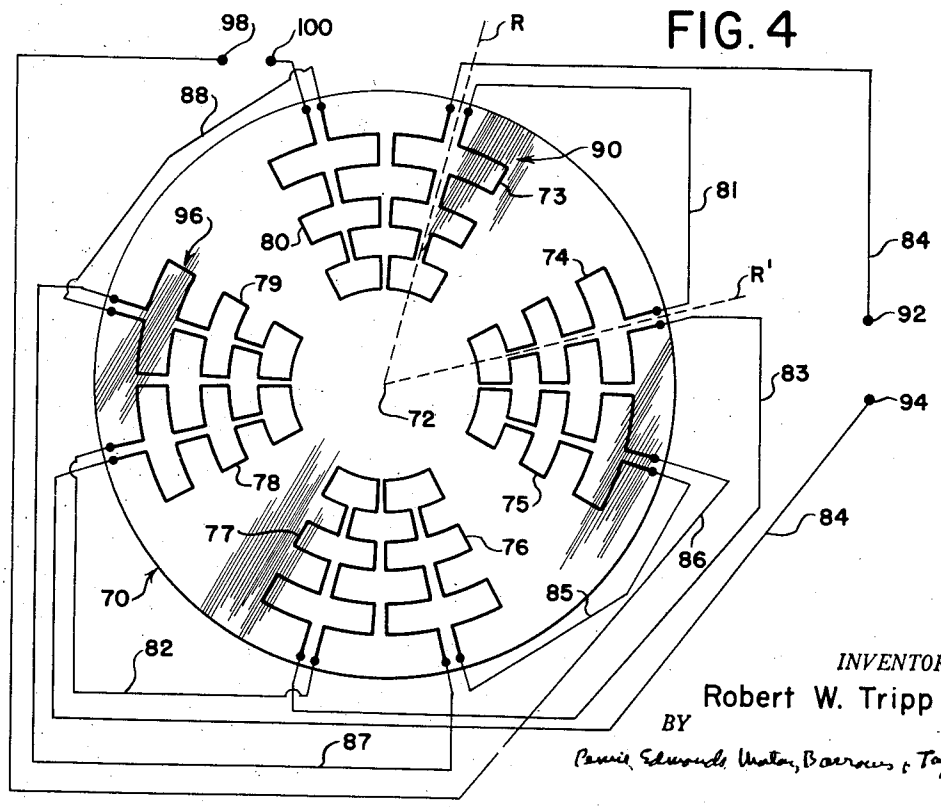


FIG. 4



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United States Patent Office 2,900,612
Patented Aug. 18, 1959

2,900,612

VARIABLE COUPLING TRANSFORMERS

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Application September 26, 1955, Serial No. 536,464

24 Claims. (Cl. 336—123)

This invention relates to transformers of adjustable coupling factor. The invention provides transformers of this type in which the coupling factor or factors are accurately known and preferably sinusoidal functions of the relative position of two relatively rotatable elements which bear the primary and secondary windings of the transformer. The transformers of the invention preferably include no ferromagnetic material and depend upon inductive coupling between closely spaced primary and secondary windings. The windings are of spiral or of spiral and other arcuate shape, mounted (usually on flat disks of insulating material) for relative rotation in a common axis which is coaxial with the axis of the spiral or other arcuate patterns to which the windings conform. The transformers of the invention are useful as synchros for angular data measurement and transmission, and especially as computing elements for the generation of voltages which represent circular functions of angular displacements between primary and secondary members. In particular the transformers of the invention find application as resolvers which can be constructed to operate with high accuracy.

The invention will now be further described in conjunction with the accompanying drawings in which:

Fig. 1 is a plan view of one transformer member (which may be either a primary or a secondary) according to the invention;

Fig. 2 is a plan view of a member similar to that of Fig. 1 but having two separate windings in space quadrature, the windings of both Figs. 1 and 2 being spiral in shape;

Fig. 3 is a plan view of another transformer member according to the invention bearing a single circularly arcuate sectoral winding;

Fig. 4 is a plan view of still another transformer member according to the invention including two windings of circularly arcuate sectorial shape in space quadrature, the two windings of the member of Fig. 4 being subdivided into sections positioned and dimensioned in order to improve the sinusoidal quality of the coupling functions between each of them and the winding or windings of a primary member according to Fig. 1 or Fig. 2 when a member according to Fig. 4 is combined with a member according to Fig. 1 or Fig. 2 into a complete transformer;

Fig. 5 is a view in side elevation of a complete transformer according to one embodiment of the invention; and

Fig. 6 is a view in side elevation of another complete transformer according to the invention.

One form of transformer according to the invention is shown in Fig. 5. It includes two disks **2** and **4** made of non-ferromagnetic insulating material, for example glass, mounted for relative rotation in an axis **6**. Either or both of the disks **2** and **4** may be rotatable with respect to the surrounding frame of reference; it is sufficient that the disks be rotatable with respect to each other. The disk **2** is shown mounted on a shaft **8** and the disk **4** is shown mounted on a shaft **10**. Of course the disks **2** and **4** need not be round in shape; the outline of the disks is immaterial, although they are advantageously round and centered on the axis of relative rotation. The disks have faces **12** and **14** which are plane and perpendicular to the axis of relative rotation **6**. The disk or disks movably mounted must be restrained against relative axial motion so that the spacing between the faces **12** and **14** will remain constant within reasonably close tolerances. These tolerances may for example be of the order of a few thousandths of an inch in a nominal disk spacing which may for example be of the same order of magnitude as the separation of adjacent convolutions of the spiral conductors which, as will presently be described, are provided on one or both disks. The disk spacing may however also be substantially smaller. In Fig. 5 the disk **2** and its shaft **8**, to which the disk **2** is affixed, are shown as mounted for rotation at bearings **16** which include a thrust surface to prevent endwise play of the disk **2**.

The faces **12** and **14** bear each one or more windings of the types illustrated in Figs. 1–4, at least one face bearing a winding of one of the types illustrated in Figs. 1 and 2, and the coupling factor or coefficient between each winding of one disk **2** and each winding of the other disk **4** varies with the angular positional relation of the disks about their axis **6**. In preferred embodiments of the invention the windings are so arranged that this coefficient is sinusoidal, going through one cycle per relative revolution of the disks.

In the transformers of the invention, there may be one or more primary windings and one or more secondary windings, all primary windings (if plural) being fixed with respect to each other and all secondary windings (if plural) being fixed with respect to each other, all primary windings being movable as a unit with respect to all secondary windings. Either winding or group of windings so fixed with respect to all other windings may serve as the primary or as the secondary winding or windings of the transformer and the terms "rotor" and "stator," if desired, may be interchangeably applied to either of such groups of relatively fixed windings and to the support therefor. Hereinafter the term "member" will be applied to any one of such groups of windings of a transformer, together with the support or supports therefor.

Transformer members according to the invention will now be described in further detail with reference to Figs. 1–4.

Fig. 1 illustrates one form of transformer member according to the invention including a single winding. In Fig. 1 a disk **18** of non-ferromagnetic and non-conducting material such as glass is provided with a plane face **20** on which there is arranged a conducting winding generally indicated at **22**. The winding **22** comprises two interlaced spirals **23** and **25** of equal and constant pitch, concentric in a point **24**. Each of the spirals includes at least one complete turn and preferably includes a number of complete turns, five or six turns being a practical minimum in the preferred embodiments of the invention in which sinusoidal coupling functions of rotor-stator angle are to be obtained. In the assembled transformer the member of Fig. 1 is mounted with point **24** on the axis of relative rotation of the transformer members and with the face **20** perpendicular to that axis. Point **24** may be referred to as the center or axis of the member, and the two spirals **23** and **25** are equiangularly disposed with respect to it, i.e. they are spaced apart by 180° of a circle around the point **24**.

In the embodiment of Fig. 1 the inner ends of the two spirals are connected together and the winding **22** which they form may be fed at terminals **26** and **28** at the radially outer ends thereof. The two halves of the winding may instead be connected in series at their outer ends, the connection being made in either case so that in adjacent convolutions of the two spirals current flows in

opposite directions, clockwise in one and counterclockwise in the other. The double spiral winding **22** so formed may be provided by photoetching of a sensitized silver surface deposited on the face **20** of the disk.

A simple form of transformer according to the invention comprises two members of the type illustrated in Fig. 1, mounted as illustrated in Fig. 5 with the windings on the adjacent faces of the two disks as so mounted. In such a case the spiral patterns of both primary and secondary windings should, when viewed in any one direction along the axis **6**, be of the same sense. Thus for example as so viewed counterclockwise rotation about the axis **6** along all spirals should result in motion radially outward from, or inward to, the axis. Moreover all of the spirals should have the same pitch.

If the two ends of the double spiral winding of one member are energized with a suitable alternating voltage for example in the upper range of audio frequencies, the magnitude of the alternating voltage induced into the winding of the other member will then be a function of the relative angular position of the two members in their axis **6** of relative rotation (Fig. 5). Slip rings may be provided on the rotating member or members for connection to the ends of the winding. Alternatively rotary transformers may be employed for this purpose, or even flexible leads if continuous rotation need not be provided for.

As the relative position of the primary and secondary members is changed, the coupling factor changes also, passing through 360° of a cycle for one complete revolution in relative position. The coefficient of coupling or coupling factor will not for this simple structure be in general a sinusoidal function of angle, but that it will be a cyclical function is clear from consideration of the fact that there are two relative positions 180° apart for the two members (the disks **2** and **4**, in terms of Fig. 5) in which the windings of the two members will be at equal and minimum separations. In these positions of maximum coupling the two double spiral windings will lie on a common spiral cylindrical surface coaxial in the axis **6** of Fig. 5. One of these positions is the position of maximum coupling in one sense while the other is the position of maximum coupling in the other sense. The positions 90° from those of maximum coupling will be at least approximately positions of minimum coupling.

The transformers of the invention find advantageous application as resolvers, employing two windings on at least the secondary member. In such resolvers a sinusoidal input voltage or voltages to one member, the primary, are resolved in the secondary member into sinusoidal voltages whose amplitudes represent the sine and cosine of the angle between primary and secondary members, measured from an arbitrary zero relative position of reference for which the amplitude in one secondary winding is zero (sine voltage) and for which the amplitude in the other secondary winding is a maximum (cosine voltage). A transformer according to the invention constituting a resolver requires in its secondary two windings whose coupling waves with respect to the primary shall be 90° out of phase. That is to say, the rotor-stator position for which the coupling wave from each primary winding to one secondary winding is at a maximum is the rotor-stator position for which the coupling wave from that primary winding to the other secondary winding is a minimum. A combination of two windings so oriented with respect to each other as to provide coupling waves so dephased is illustrated in Fig. 2. In Fig. 2, a disk **30**, which may be identical with disk **18** of Fig. 1, bears two double spiral windings **32** and **34**, each one of which may be identical with the winding **22** shown in Fig. 1. The winding **32** is displaced with respect to the winding **34** by 90° about the center point **36** in which both windings are concentric. In the embodiment illustrated, the windings **32** and **34** have a cross-over point in the vicinity of the center **36**. This may be provided by means of an insulating bridge or foil **38** laid down over a short length of one winding before the other winding is applied. Alternatively the radially outer ends of the two spirals forming each winding may be connected together, as in the embodiment of Fig. 1, by conductors on the outer periphery or back face of the disk.

An elementary form of resolver according to the invention may be provided by combining a member according to Fig. 1 with a member according to Fig. 2 in the physical relation of Fig. 5. If two input voltages are to be provided for, both members may be of the type illustrated in Fig. 2.

In transformers according to the invention either the primary or secondary member will include a winding or windings of the double spiral type illustrated in Fig. 1. While the other member may include a winding or windings of the same type, other forms of winding in which the operative portions are circular arcs may be preferred, since this makes it possible to place the leads to the two members in such position that they do not have inductive coupling between them to introduce unwanted harmonics or other components into the coupling waves. In addition, division of the winding or windings of one member into sectoral sections as will presently be described permits incorporation of a number of features which effect harmonic cancellation and balance for wobble and decentering of the disk supports of the windings.

Transformer members according to the invention employing such arcuate windings are shown in Figs. 3 and 4. Thus in Fig. 3 disk **40** bears a single winding generally indicated at **42** having terminals **44** and **46** and a plurality of inductively effective portions conforming to arcs of circles concentric in a center point **48** which, in the assembled transformer embodying the member of Fig. 3 and a member according to Fig. 1 or Fig. 2, lies on the axis of relative rotation. The arcuate portions are joined together in series by radial portions which terminate in leads to the terminuals **44** and **46**. The winding **42** includes a plurality of circularly arcuate portions **51—56**, concentric in point **48**, centered in angular extent on a common radius from the point **48**, and radially spaced from each other by one-half the pitch of either of the spiral portions of the double spiral winding or windings of the other transformer member, for convenience called the primary.

For more complete symmetry it is advantageous to position the radial leads between the successive arcuate portions **51—56** symmetrically with respect to the length of those arcuate portions themselves so that, as indicated in Fig. 3, each of the portions **51—56** has associated therewith an equal portion **51′—56′** of the same radius and arcuate length, arranged to conduct in the same clockwise or counterclockwise sense as its mating portion. Hereinafter reference to the arcuate portions **51—56** will be understood to refer to the sum of the portions **51** and **51′**, **52** and **52′**, etc. It is however possible to locate the radial leads at one end of the arcuate portions, one radial lead being continuous.

There must be in the secondary winding **42** at least one arcuate portion, and there are preferably several of them, six or eight for example, the number of spiral convolutions in the winding or windings of the primary member being sufficient so that each spiral extends preferably at least one complete turn beyond the outermost and beyond the innermost of the arcuate portions of the secondary member in order to minimize the effect of inhomogeneities in the field adjacent the inner and outer ends of the spirals of the primary.

The angular extent of the arcuate portions of such a winding as is illustrated in Fig. 3 may be chosen within rather wide limits. In preferred embodiments of the invention this angular extent will be rather small, of the

order of 60°, as will be explained presently. All arcuate portions centered on a common radius are preferably of equiangular extent about their common center of curvature. So long however as the angular extent of the arcuate portions is less than 360° there will for all but two relative positions of the primary and secondary members and for any given excitation of a primary winding be induced in each arcuate portion of the secondary a net voltage, i.e. the coupling factor will not be zero. The coupling factor of any one arcuate portion of the winding of Fig. 3 to any one winding of a primary member according to Fig. 1 or Fig. 2 will have a maximum of one sign when, approximately, the mid-point of that portion is at its nearest approach to one of the spirals of the primary winding under consideration, and the coupling factor will have its maximum value of opposite sign at the relative position 180° from that just considered. Since the pitch of the arcuate portions is one-half that of the spiral windings of the primary member and since successive arcuate portions of the secondary winding **42** are series connected so that radially successive portions thereof carry current in opposite directions, clockwise and counterclockwise about the axis, the voltages induced in all of the arcuate portions add. It is clear that the coupling wave between the series-connected portions **51—56** and one of the double spiral windings of the member of Fig. 2 will be 90° displaced in phase from the coupling wave between those portions and the other double spiral winding of the primary according to Fig. 2.

In Fig. 3 the complete winding 42 includes not only the arcuate portions **51—56** but a duplicate set of arcuate portions **61—66** positioned 180° from the first. The portions **61—66** are connected together in series in exactly the same way as are the portions 51—58, each set of arcs forming what may be called a section of the winding **42**. In Fig. 3 the first section is identified by the reference character **59** while the second section is identified by the reference character **69**. Since the coupling waves between any one rotor winding (either of the windings 32 and **34** of Fig. 2) and the section 59 is 180° displaced from the coupling wave between the same rotor winding and the section **69**, reenforcement of the coupling waves to the two sections of the secondary winding of Fig. 3 is obtained by crossing on or near the axis 43 the radial conductors by which the two sections are connected in series. Along with other advantages to be described presently, provision of two series-connected sections in the winding **42** obviously increases the magnitude of the coupling factor, which is low in maximum value even at best.

In general, the coupling wave or waves observed with the transformers of the invention as thus far described, are not accurately sinusoidal. Appreciable harmonic content may be expected to be present even if the inevitable departures of the winding patterns from perfect geometry, decentering thereof and wobble due to non-perpendicularity of the disk faces in the transformer axis were removed. The harmonics present in the coupling waves are primarily of odd order since the symmetry of the members makes the coupling waves symmetric about their maximum and minimum values.

In their preferred embodiments the transformers of the invention and hence the members of which those transformers are made include features of construction in the dimensioning and disposition of the windings which minimize harmonics in the coupling waves. The member of Fig. 3 incorporates one form of harmonic compensation according to the invention. In the embodiment of Fig. 3 the third harmonic of the coupling wave to the single winding of that figure is minimized by employing in that member arcuate portions of 120° angular extent. By making the sections **59** and **69** 120° in extent each, each arcuate portion in each section extends over one-third of the radial cycle of each of the windings in the primary member according to Fig. 1 or Fig. 2. Each such arcuate portion therefore extends over a whole cycle of the third harmonic in the coupling wave between either primary winding and that arcuate portion. Consequently for all rotor-stator positions in a transformer including a member according to Fig. 3, the sum of the voltages induced instantaneously in any arcuate portion of the winding of Fig. 3 includes all phases of any third harmonic in the coupling wave, and the third harmonic in the coupling wave to each such arcuate portion is therefore zero. More generally, cancellation of any desired harmonic may be obtained by the use of sections including circularly arcuate portions concentric in the transformer axis whose angular extent, expressed as a fraction of 360°, is the reciprocal of the order of the harmonic to be suppressed. Thus the fifth harmonic may be suppressed by sectors of 72° angular extent. When arcuate windings of the type illustrated in Fig. 3 are employed, with or without harmonic suppression, it is desirable to provide two diametrically opposite series-connected sectors as illustrated in Fig. 3. This not only improves the coupling factor but effects compensation for decentering of the center **48** from the axis of rotation when the member according to Fig. 3 is combined with a primary member into relatively rotatable relation in a transformer. Provision of diametrically opposite sectors also compensates at least partially for wobble, i.e. non-perpendicularity of the plane of the disk **40** to that axis. Provision of such diametrically opposite sectors is however not necessary. Transformers according to the invention analogous to the usual self-synchronous motors and generators may be provided from a single winding rotor according to Fig. 1 and a three-phase stator including three equiangularly disposed separate secondary sectoral arcuate winding similar to the sectors **59** and **69** of Fig. 3.

The embodiment of Fig. 3 includes only a single winding, and even if the second section of that winding were suppressed the 120° extent of the first section **59** would preclude the provision of another separate winding of the same shape in space quadrature with the first without overlapping. Hence other winding patterns are desirable for embodiments of the invention such as resolvers in which it is desired to have two windings in space quadrature on both members of the transformer. Fig. 4 illustrates a transformer member according to the invention suitable for use with a member according to Fig. 2 to provide such a transformer with two primary and two secondary windings.

On the member of Fig. 4 there are provided two windings in space quadrature, and these windings are subdivided into sections which are dimensioned and located with respect to each other in such a fashion as to compensate for the third and twelfth harmonics in the coupling waves and also to compensate for wobbling and decentering errors. The member of Fig. 4 includes a disk **70** intended to be mounted for rotation in an axis perpendicular to the face of the disk seen in the figure. 72 identifies the point on the disk face on which the conductor patterns are concentric. There are provided on the disk eight conducting patterns or winding sections **73—80**, all of the same general type as the sections **59** and **69** of Fig. 3. All of the sections are of 30° angular extent, and successive sections are centered on radii which are alternately 60° and 30° apart, so that two sections centered on radii 60° apart are provided in each quadrant of the disk face. Each of the sections includes a plurality of circularly arcuate portions concentric in the center **72**. Each section has two terminals, at the periphery of the disk in Fig. 4. The sections are there connected together in series in two groups to form two windings in space quadrature. The sections **73** and **74** fall within one quadrant of the disk

face and together with the sections 77 and 78 in the diametrically opposite quadrant form one of the two quadrature windings. Provision of radially opposite symmetric winding sections effects cancellation of wobble and decentering errors as in the embodiment of Fig. 3. Moreover the sections 73 and 74 are symmetric respectively in two radii R and R' of the disk face, 60° apart. Consequently the third harmonic component of the coupling wave between any primary winding and the section 73 is half of a third harmonic cycle displaced in phase from the third harmonic component of the coupling wave between the same primary winding and the section 74. Accordingly cancellation of the third harmonic may be effected by connecting sections 73 and 74 in series, and similarly cancellation of the third harmonic may be obtained between sections 77 and 78. In order that the sections 73 and 74 be symmetric in the radii R and R' and yet together occupy no more than one quadrant of the disk face, as is necessary if two separate but identical windings are to be provided in space quadrature without overlapping, the sections 73 and 74 (and also sections 75—80) are limited to 30° of angular extent. A 30° angular dimension for these sections provides compensation of the twelfth harmonic of the coupling waves by virtue of the same effect as that which in the member of Fig. 3 is operative to provide third harmonic compensation.

The series connection of sections 73 and 74 is, as indicated by the external lead 81, such as to give reenforcement between the fundamental component of the coupling waves to each of these sections.

The same precaution is observed in the series interconnection of sections 77 and 78 in the opposite quadrant as is indicated by lead 82. In connecting together in series sections 73, 74 on the one hand and 77, 78 on the other, a reversal is made by means of leads 83 and 84 because of the 180° phase difference between the fundamental component of the coupling wave from any primary winding to a secondary in one quadrant and the fundamental component of the coupling wave from that primary to a secondary winding in the opposite quadrant. The first winding of the transformer member of Fig. 4, comprising sections 73, 74, 77, 78, is generally indicated by the reference character 90, and possesses two terminals 92 and 94 in lead 84. In a similar manner leads 85—88 interconnect sections 75, 76 and 79, 80 into a single series circuit to develop the second winding of the transformer member of Fig. 4, generally indicated at 96 and having terminals 98 and 100. The leads interconnecting the sections 73—80 have been indicated diagrammatically only. They may be placed on the peripheral edge or back face of the disk.

When harmonic compensation is effected as in the member of Fig. 4 with respect to the third harmonic by series interconnection of two circumferentially displaced sectoral winding sections to form a winding or part of a winding, there is a difference in phase between the fundamental components of the separate coupling waves between any winding of the other transformer member and those sections. Consequently, the coupling wave for the two sections in series together is different in phase from the coupling in either section alone and has an amplitude given by the vector sum of the amplitudes of the separate coupling waves to each section. The separate coupling waves reinforce each other, however, since their phase difference is less than 90°.

Further suppression of harmonics may be achieved by a suitable dimensioning of the width of the conductors with respect to the space between immediately adjacent geometrically parallel series-connected portions thereof which carry the same current in opposite directions, in accordance with the disclosure and claims of the copending application Serial No. 509,168, now Patent No. 2,799,835, assigned to the assignee hereof, filed May 18, 1955. This method of harmonic suppression is applicable separately to transformer members according to Figs. 1 and 2, which members have windings including spiral portions of one complete revolution or more, and also to members of the type illustrated in Figs. 3 and 4, which members have arcuate windings of lesser angular extent. Any one harmonic may be canceled in a transformer made up of members of these types by application of this technique to one of the two transformer members. Another harmonic may be canceled by application of the technique to the other transformer member.

According to this technique as applied to the member of Fig. 1 for example, the third harmonic may be eliminated by making the width of the conductors of the one double spiral winding in that member twice the space between radially adjacent portions of that winding, i.e., between adjacent portions of the individual spiral conductors 23 and 25, so that the conductor width will be two thirds of the cycle comprising one conductor and the space which separates it from an adjacent conductor carrying the same current in the opposite direction. As applied to members of the type illustrated in Figs. 3 and 4, elimination of the third harmonic by this technique requires that the width of the arcuate conductors be two thirds of the cycle comprising each such arcuate conductor and the space which separates it from an adjacent arcuate conductor, which carries the same current in the opposite direction. In a transformer including a member according to Fig. 2, the third harmonic cannot be eliminated by applying this technique to such a member because of the presence of two double spiral windings interlaced with each other and carrying different currents. The fifth harmonic may, however, be eliminated on such a member by making the width of each conductor two fifths of the cycle comprising one conductor and the space which separates it from the radially adjacent conductor of the same winding, i.e., that which carries the same current but in the opposite direction. The three fifths of the cycle not occupied by the conductor of one winding leave room for a similarly dimensioned conductor of the other winding. Of course, this same criterion may be applied to a single winding member according to Fig. 1, or to members of the type of Figs. 3 and 4, in order to suppress the fifth harmonic.

Transformers according to the invention satisfactory for angular data transmission of the type effected with self-synchronous motors and generators do not require sinusoidal coupling waves. The transformers of the invention however find application as resolvers in computing apparatus in which it is desirable that the absolute magnitudes of the voltages induced by the primary winding or windings into the secondaries be individually sine and cosine functions of rotor-stator angle. In order to achieve this result it is necessary not only to suppress harmonics in the coupling waves but to maintain constant the axial spacing between primary and secondary members, to variations in which the coupling factor is sensitive, or else compensation must be provided for variations in coupling function due to variations in that spacing.

To this end applicant has provided as a presently preferred embodiment of his invention a transformer as illustrated in Fig. 6, designed to serve as a resolver with two input windings in quadrature and two output windings in quadrature. The transformer of Fig. 6 comprises a shaft 110 on which is mounted a rotor disk 112, of insulating material as before, and two stator members or disks 114 and 116 likewise of insulating material. The shaft 110, which passes through central apertures in disks 114 and 116, is mounted in bearings 118 and 120 to define an axis of revolution 122 for the rotor, with which the shaft and rotor disk are dimensioned and fitted to rotate concentrically as nearly as practicable, with the faces of the rotor and stator disks perpendicular to this axis. The bearings 118 and 120 moreover include a thrust element to limit within reasonably close tolerances play of the rotor 112 lengthwise of the axis 122.

The rotor disk **112** advantageously bears on each of its faces two double spiral windings as illustrated in Fig. 2, and each stator disk bears two arcuate windings as illustrated in Fig. 4. The four rotor windings are combined in pairs and the four stator windings are also combined in pairs to provide for the resolver two "resolver windings" in space quadrature fixed with respect to the shaft **110** and two "resolver windings" in space quadrature fixed with respect to the frame of reference in which the stator disks are mounted. Each of these pairs of stator windings includes one winding from disk **114** and one from disk **116**, and each of these pairs of rotor windings includes a winding from each face of the rotor disk **112**, disk **112** providing in substance two transformer members according to Fig. 2 and each of stator disks **114** and **116** providing a transformer member according to Fig. 4.

The two halves of each such resolver winding may be connected in series or in parallel with each other. In the case of a resolver winding serving as a primary, it is desirable that the two halves thereof be connected in series with each other in order that the same current flow through both.

The spiral windings according to Fig. 2 on the two faces of the rotor disk **112** may be of the same or opposite hand, a suitable selection of end points of the eight windings (in the sense of the windings of Figs. 2 and 4) for interconnection by pairs into the four resolver windings permitting in either event the achievement of reinforcement of the coupling waves obtained.

The resolver of Fig. 6 will exhibit coupling functions which are independent of the small amount of end play of the rotor shaft which must be allowed for in the manufacture of a mechanical device, since the decrease in coupling between one pair of rotor and stator resolver windings upon endwise motion of the rotor in one direction will be balanced by an increase in coupling between the other pair of resolver windings.

The resolver of Fig. 6 may incorporate any and all of the features of construction for compensation of harmonics and of wobble and decentering errors which have been discussed hereinabove. By comparison with a transformer according to Fig. 5, a transformer according to Fig. 6 provides an additional possibility for harmonic compensation in the resulting combined coupling waves in the same manner essentially as that described in connection with Fig. 4. Thus if the spiral patterns on the two faces of disk **112** are phased together, i.e. similarly positioned about the axis **112** and if the conducting patterns on disks **114** and **116** are displaced from each other by 60° about the axis **122**, the fundamental components of the coupling waves attributable one to each half of the resolver as a whole will be 60° apart, and upon combination of these two waves cancellation of the third harmonic in the resultant over-all coupling wave will be effected. This is not, however, the principal advantage to be obtained from the use of a transformer according to Fig. 6 in place of one according to Fig. 5.

In one design of a resolver according to Fig. 6 the double spiral windings from both faces of the disk **112** combined in pairs to provide two resolver windings were so chosen that each such pair included two windings 90° apart, and a similar choice was made in combining the four stator windings of the type shown in Fig. 4 in pairs to form the two stationary resolver windings, in order to help balance residual effects of wobble, decentering, and axial displacement of the rotor on the absolute value of the coupling between rotor and stator.

The invention has been described hereinabove in terms of presently preferred embodiments thereof. Various changes and departures from the particular structures which have been described may however be made within the scope of the invention. For example, the transformer members of Figs. 3 and 4 have been described as having windings comprising arcs of circles concentric with the axis of rotation of the transformers in which the members are to be employed. Transformers according to the invention may however be constructed with members of the general type illustrated in Figs. 3 and 4 but in which the arcs are arcs of spirals rather than circles, or arcs of circles not individually concentric in the intended axis of rotation of the member. The essential property for the achievement of harmonic compensation according to the method described in connection with Fig. 3 is that of the two conductors in inductive relationship, one (for convenience here assumed to be the secondary) should include a portion having a spiral pitch not identical in amount and sign to the pitch of the conductor which is of the spiral type illustrated in Fig. 1 (for convenience here assumed to be the primary). The circularly arcuate conductors of Figs. 3 and 4 may be regarded as spirals of zero pitch. With such non-identity of pitch the secondary conductor may be dimensioned and positioned to span a simple fraction of one cycle of the spiral magnetic field of the primary member, such fraction being an integral number of multiples of the reciprocal of the order of the harmonic in the coupling wave sought to be suppressed. It will be understood that on the primary member each pair of radially adjacent series-connected spiral conductors carrying the same current in opposite directions will generate (if energized) a spiral field having one spiral pole of each polarity. When as in Figs. 1 and 2 the two series-connected spiral conductors are 180° apart, there are two such fields or half fields interlaced back to back and of equal radial dimensions. These two spiral fields may be thought of as constituting a single fully cyclical spiral field, the spatial pole cycle of which extends from a pole of one sign opposite one spiral conductor to a pole of the same sign opposite the adjacent convolution of the same spiral conductor, i.e. the radially adjacent conductor carrying the same current in the same direction. The spiral pitch of this cyclic magnetic field is therefore, in the embodiments illustrated in Figs. 1 and 2, equal to the geometrical pitch of the spiral conductors which give rise to it. Therefore in transformers including a member as illustrated in Fig. 1 or 2, for compensation according to the principle illustrated in Fig. 3, the ends of the inductively effective portions of the secondary conductors thereof (as distinguished from the radial connecting portions, in the embodiments of Figs. 3 and 4 for example) should have as their points of nearest approach in the plane of the primary winding or windings points which in that plane differ in the phase of the primary conductor pitch cycle by a simple fraction as above defined. Of course also, in order to be inductively effective, these portions of the secondary should have a component of length parallel to the length of the primary.

With the inductively active portions of the secondary windings taking the form of circular arcs concentric of the transformer axis as in Figs. 3 and 4, and with the two-spiral winding members of Figs. 1 and 2, the angle subtended by these arcs on that axis is the same fraction of 360° as is the fraction of the conductor pitch cycle on the primary winding covered by those arcs individually, so that compensation according to the method illustrated in Fig. 3 is obtained with such circular arcs by giving to them an angular extent which is the same fraction of 360° as the reciprocal of the order of the harmonic to be suppressed. However, if spiral arcs or circular arcs not so concentric in the transformer axis are employed, it is possible to compensate for a harmonic of any given order with arcs which subtend at the axis of the transformer a smaller or larger angle than that defined by the fraction of 360° which is equal to the reciprocal of the order of the harmonic in question. Indeed, suitable spiraling of the arcs of the secondary member permits averaging, and hence compensation, for any desired harmonic with any given angular extent for the stator sectors subtended at the transformer axis. Circularly arcuate secondary

windings have primarily the advantage of ease in generation of the master patterns therefor.

Also, in the description of Figs. 3 and 4, it has been stated that the radial separation of successive arcuate portions is constant, and that the plural sections connected together, such as sections 59 and 69 of Fig. 3 or 73 and 74 of Fig. 4, are identical and identically placed. These conditions need not be strictly fulfilled in the transformers of the invention, and indeed it may be desirable to make intentional departures therefrom.

In said copending application Serial No. 509,168, filed May 18, 1955, and assigned to the assignee hereof, there are described transformers of other types in which both primary and secondary members include a very large number of poles, as contrasted with the relatively small number of poles in the transformers of the present application, the member of Fig. 1, for example, exhibiting along any radius one north and one south pole for each passage of either of the spirals 23 and 25 across that radius. Of course, the polarity of these poles is reversed in time with every half cycle of the excitation signal. In the transformers of said copending application last referred to suppression of the harmonics in the coupling wave is effected by a variation, either lumped or continuous, in the pole pitch of one winding by comparison with the pole pitch of another winding with which the first is in inductive relation, one of these being a primary and the other a secondary. Possibly suppression of harmonics might be undertaken in the transformers of the present invention by the same or similar methods. Thus in a member according to Fig. 3 of the present application, the radial separation of successive arcuate conductors in the section 59 might be made slightly different from one half the pitch of the spirals of the winding or windings of the associated member or members according to Fig. 1 or 2 with which the modified member according to Fig. 3 was to be used, this modification in relative pitch of the two members being such that the total ingredient of a given harmonic induced in the section 59 would add to zero. The variation in length of the arcuate conductors of the section 59 would theoretically, however, suggest a nonlinear change in pitch relationship between the primary and secondary members with radius, which might be difficult to execute.

Somewhat similarly, the two series-connected sections 59 and 69 of Fig. 3 might be located at unequal distances from the center 48 in order to position them at unlike phases of a selected harmonic in the pitch cycle of the primary of a member according to Fig. 1 or Fig. 2. Here also, however, since the effective area of a section varies with its radial location, a proper selection of such displaced radial positions appears to be difficult.

Also, compensation according to Fig. 3 and the modifications thereof which have been described may be achieved, on members such as those of Figs. 3 and 4, with respect to any given harmonic by means of arcuate conductors which span, on the other transformer member of the Fig. 1 or 2 type, fractions of the pitch cycle of the spiral windings of the latter member amounting to an integral number of cycles of the harmonic in question even though this integral number is greater than one. Thus in the embodiment of Fig. 3 itself, while each of the circular arcs 51—56 and 61—66 subtends 120° and therefore spans, on a transformer member according to Fig. 1 or Fig. 2 to be associated with a member according to Fig. 3, one third of the spiral pitch cycle of either of the windings of Fig. 2 and hence a single cycle of the third harmonic in the coupling waves, each of those arcs also spans two complete cycles of the sixth harmonic, three cycles of the ninth and so on, providing compensation as to these other harmonics as well.

In the preferred embodiments of the invention which have been described herein, the coupling wave or waves between the two transformer members go through one complete cycle per revolution of the members with respect to each other in their axis of relative rotation. This is due to the nature of the spiral windings illustrated in Figs. 1 and 2, each of these windings including two series-connected spirals displaced from each other by 180° about the center of the disk face on which they are provided. With such a pattern one revolution of the disk exposes a point, conceived as fixed in a plane adjacent the plane of such a winding, to one complete cycle of positions relative to such a double spiral winding.

The invention is not however limited to such structures. Transformers according to the invention can be constructed with any desired number of coupling cycles per revolution. For example, starting with a given member according to Fig. 3 or 4, a transformer having three coupling cycles per revolution may be produced by providing a spiral member having six equiangularly spaced spiral conductors whose spiral pitch is six times the radial separation of adjacent arcuate conductors on the member according to Fig. 3 or 4. Adjacent inner ends of the spirals are then connected together in pairs, and adjacent outer ends are also connected together in pairs to produce a six-spiral winding. If a second winding in quadrature is to be provided on the spiral member, its six spiral conductors are arranged half way between the spirals of the first winding so that the member will bear in all twelve spiral conductors 30° apart about the center of the disk. In general, a transformer with n cycles for its coupling waves per revolution of the transformer members may be provided by means of a spiral member having, for each winding thereon, $2n$ equiangularly disposed spiral conductors connected in series. Indeed a transformer according to the invention can be constructed to operate over a portion of one revolution in relative position of its members with a spiral member having a plurality of spiral conductors which (if, as will usually be desirable, more than two are provided) are spaced from each other by equal angular intervals about the disk center but which do not cover the whole face of the disk, for example if the angular separation of adjacent spirals is incommensurable in 360°. With all of these constructions the coupling wave from each spiral winding of the spiral member to each winding of the other member will go through 180° of phase for a relative rotation of the two transformer members equal to the angular spacing of two adjacent series-connected spiral conductors in each winding of the spiral member.

In all, the geometrical pitch of the spiral conductors should be such that, in an angular advance on the spiral member equal to that over which the coupling wave is to go through 360°, the radius of the spirals will change by the spacing center to center of three arcuate conductors in one of the sectoral sections on the member of the transformer according to Fig. 3 or 4, i.e. by two arcuate conductor intervals. Thus in a transformer having one cycle per revolution the pitch of the spiral conductors, e.g. those shown in Figs. 1 and 2, is such that the radius of each spiral changes by two arcuate conductor intervals in 360 geometrical degrees of advance. Similarly in a transformer having for its coupling waves two cycles per revolution and therefore having series-connected spiral conductors 90° apart (preferably four of them) in each winding of its spiral member, the pitch of the spiral conductors is such that the radius of each spiral advances by two arcuate conductor intervals in 180 geometrical degrees of advance.

With transformers having more than one coupling cycle per revolution, the dimensioning and/or disposition of the arcuate conductors on the transformer member according to Fig. 3 or 4 should be appropriately altered if harmonic compensation is to be obtained by the means described in connection with those figures.

It has been stated that, for compensation according to the method of Fig. 3, the ends of each arcuate conductor should have as their points of nearest approach to the plane of the spiral member points which in that plane,

and at their respective circumferential positions, differ in the phase of the spiral magnetic field of the primary member by a fraction of the radial length of that magnetic field equal to the reciprocal of the order of the harmonic to be suppressed (or by a multiple of that fraction). With circularly arcuate conductors as illustrated in Fig. 3 this means for a transformer having one coupling cycle per revolution that the arcuate conductors in the member according to Fig. 3 should subtend at the center of the disk on which they are mounted an angle equal to the fraction of 360° whose reciprocal is the order of the harmonic to be suppressed.

With respect to the additional compensation illustrated in Fig. 4, the two series-connected sectoral sections between which compensation is effected are centered on bearings which are spaced by an angle equal to the angle over which the phase of the harmonic component in the coupling wave which is to be suppressed changes by 180°.

With transformers according to the invention in which the coupling wave goes through 360° of phase for a lesser number of degrees of rotation the corresponding dimensions of the arcuate conductors on the member according to Fig. 3 or 4 must be proportionally reduced. If the transformer has two coupling wave cycles per revolution and includes a member according to Fig. 3, including circularly arcuate conductors concentric with the axis of disk rotation, the arcuate extent of these arcuate conductors should be reduced by a factor of two. Likewise in a member according to Fig. 4 for use in such a transformer having two coupling wave cycles per revolution, the angular separation of the series-connected sectoral sectors should be reduced by a factor of two. It will be remembered that in such a transformer the spirals are twice as steep, for the same pitch of the arcuate conductors, as in a transformer having one coupling wave cycle per revolution. Hence the phase of the spiral magnetic fields changes twice as fast with angle around the center of the disk.

More generally stated, for compensation of harmonics in the coupling wave according to the principles described hereinabove in connection with Fig. 3 but in transformers having a number of coupling wave cycles per revolution other than one, the points in the plane of the spiral member nearest the ends of the arcuate conductors employed for such compensation should differ in the phase of the geometrical pitch cycle of the spiral conductors on the primary member by a fraction which is related to the harmonic to be suppressed as hereinabove explained in connection with transformers having one coupling wave cycle per revolution except that in the transformers now under consideration the number of coupling wave cycles per revolution appears as a factor in the denominator of that fraction. Indeed this number always so appears, the factor being unity for transformers having one coupling wave cycle per revolution. The same principles apply to the provision of compensation according to the method illustrated in Fig. 4, in transformers having a number of coupling wave cycles per revolution other than unity.

In similar fashion the angular separation of two windings on any one transformer member which are to be in space quadrature is inversely proportional to the number of coupling wave cycles per revolution, quadrature meaning quadrature of the angular interval over which the coupling wave goes through one cycle. Thus if the transformer includes on its spiral member $2n$ equiangularly disposed spiral conductors in one winding so as to have $360/n$ cycles in its coupling waves per relative revolution of the transformer members, the angular separation on either member of two windings which are to be in space quadrature should be $360/4n$.

I claim:

1. A transformer comprising two members having each a plane face, means to support said members with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, two spiral conductors of equal and constant pitch disposed on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly positioned ends thereof, and a conductor disposed on the other of said faces, said last-named conductor including a portion conforming to an arc of a curve coaxial of said axis.

2. A transformer comprising two supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, two spiral conductors of equal and constant pitch disposed on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly positioned ends thereof, and a conductor disposed on the other of said faces, said last-named conductor including a portion conforming to an arc of a spiral coaxial of said axis.

3. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, an even plurality of spiral conductors of the same pitch equiangularly disposed on one of said faces coaxially of said axis, circumferentially adjacent of said conductors being connected in series at radially similarly positioned ends thereof to produce a series winding including all conductors of said plurality, and a winding disposed on the other of said faces, said last-named winding including a plurality of series-connected arcuate conductors equiangularly disposed with respect to each other about said axis.

4. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, a plurality of spiral conductors of equal and constant pitch disposed on one of said faces coaxially of said axis, each of said conductors being spaced from at least one other of said conductors by the same angular interval about said axis, said conductors being connected in series at radially similarly positioned ends thereof to form said conductors into a two-terminal series winding, and a conductor disposed on the other of said faces, said last-named conductor including a portion whose ends have as their points of nearest approach in the plane of said spiral conductors points differing in phase of the pitch cycle of any of said spiral conductors by a fraction of the pitch of any of said spiral conductors.

5. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, two spiral conductors of the same pitch equiangularly disposed on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly positioned ends thereof, and a conductor disposed on the other of said faces, said last-named conductor including a portion conforming to a circular arc coaxial with said axis and subtending at said axis an angle equal to a simple fraction of 360° whose denominator is a small integer.

6. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation about an axis perpendicular to said faces, two spiral conductors of equal and constant pitch equiangularly disposed on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly disposed ends thereof, and a winding on the other of said faces, said winding including a plurality of series-connected arcuate portions coaxial in said axis, successive of said portions being radially spaced by one-half the pitch of said spiral conductors.

7. A transformer comprising two insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a

substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, two spiral conductors of equal and constant pitch equiangularly arranged on one of said faces coaxially of said axis, said conductors being connected in series so that radially adjacent convolutions thereof carry current in opposite directions, and a winding on the other of said faces including a plurality of series-connected circularly arcuate portions coaxial in said axis, successive of said portions being radially spaced by one-half the pitch of said spiral conductors, all of said portions subtending the same angle at said axis and being centered on a common radius from said axis, said angle being a fraction of 360° whose reciprocal is a small integer.

8. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, two spiral conductors of equal and constant pitch equi-angularly arranged on each of said faces coaxially of said axis, all of said conductors having the same pitch, the conductors on each of said faces being connected in series so that radially adjacent convolutions thereof carry current in opposite directions, all of said conductors spiraling in the same sense about said axis as viewed in one direction along said axis.

9. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, two spiral conductors of equal and constant pitch equiangularly arranged on one of said faces coaxially of said axis, said conductors being connected in series so that radially adjacent convolutions thereof carry current in opposite directions, and two windings arranged on the other of said faces coaxially of said axis, said last-named windings extending circumferentially of said other face and being disposed in space quadrature.

10. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, four spiral conductors of equal and constant pitch equiangularly arranged on one of said faces coaxially of said axis, opposite of said conductors being connected in series at radially similarly disposed ends thereof, and a winding on the other of said faces, said winding including a plurality of series-connected arcuate portions coaxial in said axis, successive of said portions being radially spaced by one-half the pitch of any one of said four spiral conductors.

11. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, two spiral conductors of equal and constant pitch equiangularly arranged on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly disposed ends thereof, and a winding on the other of said faces having two series-connected parts, each of said parts including a plurality of series-connected arcuate portions radially spaced by substantially one-half the pitch of either of said spiral conductors, the said portions of each of said parts extending circumferentially of said second face symmetrically about a common radius, said radii being separated by a simple fraction of 360° having small integers as numerator and denominator.

12. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, two spiral conductors of equal and constant pitch equi-angularly arranged on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly disposed ends thereof, and two windings in space quadrature on said second face, each of said windings comprising two series-connected parts, each of said parts including a plurality of arcuate portions occupying a sectoral area about said axis, the sectoral areas occupied by said series-connected parts being substantially centered on radii from said axis separated by an angle which is a simple fraction of 360° having small integers as numerator and denominator.

13. A transformer comprising three insulating supports, two of said supports having each a plane face and the third of said members having two parallel plane faces, means to support said first two supports with their faces parallel and at a fixed separation and to support said third support between said first two supports for rotation about an axis perpendicular to the faces of said three supports and with a substantially constant and equal spacing between said third support and each of said first and second supports, four spiral conductors of constant and equal pitch equiangularly arranged on each face of said third support, opposite of said conductors on each face of said third support being connected in series at points thereof substantially equidistant from said axis, interconnections between each pair of series-connected conductors on one face of said third support and one pair of series-connected conductors on the other face of said third support to form two windings having spiral conductors, eight sectoral windings on each of said first and second support, each of said eight windings comprising a plurality of series-connected circularly arcuate portions successive ones of which are radially spaced by one-half the pitch of each of said spiral conductors, all of said portions subtending substantially 30° on said axis and all portions of each of said eight windings being centered on a common radius, successive of said radii being alternately 60° and 30° apart, means connecting in series those of said eight windings 60° apart and further connecting in series those of said eight windings 180° apart to form two windings in space quadrature on each of said first and second supports, and interconnections between said last-named windings in pairs, each of said pairs including one of said last-named windings from each of said first and second supports.

14. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, two spiral conductors of the same pitch equiangularly disposed on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly positioned ends thereof, and a plurality of windings equiangularly disposed on the other of said faces, each of said windings including a plurality of series-connected arcuate portions, successive of said portions being radially spaced by one-half the pitch of said spiral conductors.

15. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, two spiral conductors of equal and constant pitch equiangularly arranged on one of said faces coaxially of said axis, said conductors being connected in series so that radially adjacent convolutions thereof carry current in opposite directions, and two windings arranged in spaced quadrature on the other of said faces, said last-named windings extending circumferentially of said axis.

16. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, two spiral conductors of the same pitch equiangularly disposed on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly positioned ends thereof, and a winding disposed on the other of said faces, said winding including two series-connected sections equiangularly disposed about said axis, each of said sections including a plurality of series-connected arcuate portions, successive of said portions being radially spaced by one-half the pitch of said spiral conductors, all of said portions in any one of said sections subtending the same angle at said axis and being centered on a common radius from said axis.

17. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, two spiral conductors of the same pitch equiangularly disposed on one of said faces coaxially of said axis, said conductors being connected in series at radially similarly positioned ends thereof, and two windings disposed in space quadrature on the other of said faces, each of said windings including two series-connected sections equiangularly disposed about said axis, each of said sections including a plurality of series-connected portions, successive of said portions being radially spaced by one-half the pitch of said spiral conductors, all of said portions in any one of said sections subtending the same angle at said axis and being centered on a common radius from said axis.

18. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, four spiral conductors of equal and constant pitch equiangularly arranged on one of said faces coaxially of said axis, opposite of said conductors being connected in series at radially similarly disposed ends thereof, and two windings arranged in space quadrature on the other of said faces, each of said windings including two series-connected sections, each of said sections including a plurality of series-connected arcuate portions, successive of said portions being radially spaced by one-half the pitch of said spiral conductors, all of said portions in any one of said sections being centered on a common radius from said axis, the said radii of series-connected ones of said sections being separated by an angle which is a simple fraction of 360° having small integers as numerator and denominator.

19. A transformer comprising first and second insulating supports having each a plane face, means to support said supports, with their said faces parallel to each other and with a substantially constant spacing therebetween, for relative rotation about an axis perpendicular to said faces, four spiral conductors of equal and constant pitch equiangularly arranged on one of said faces coaxially of said axis, opposite of said conductors being connected in series at radially similarly disposed ends thereof, and two windings arranged in space quadrature on the other of said faces, each of said windings including two series-connected sections disposed 180° apart about said axis, of said sections including a plurality of series-connected arcuate portions, successive of said portions being radially spaced by one-half the pitch of said spiral conductors, all of said portions in any one of said sections being centered on a common radius from said axis.

20. A transformer comprising two supports having each a plane face, means to support said supports with their faces parallel to each other for relative rotation in an axis perpendicular to said faces, a winding disposed on one of said faces, said winding including a plurality of arcuate conductors extending across a common bearing about said axis, said arcuate conductors having on said bearing substantially uniform spacing radially from said axis, said arcuate conductors being so connected in series that radially adjacent of said arcuate conductors carry current in circumferentially opposite directions about said axis, and a plurality of spiral conductors of equal and constant pitch disposed on the other of said faces coaxially of said axis, each of said spiral conductors being spaced from at least one other of said spiral conductors by the same angular interval about said axis, circumferentially adjacent of said spiral conductors being connected in series at radially similarly positioned ends thereof to form said spiral conductors into a two-terminal series winding.

21. A transformer comprising two supports having each a plane face, means to support said supports with their faces parallel to each other for relative rotation in an axis perpendicular to said faces, a winding disposed on one of said faces, said winding including a plurality of arcuate conductors extending across a common bearing about said axis, said arcuate conductors having on said bearing substantially uniform spacing radially from said axis, said arcuate conductors being so connected in series that radially adjacent of said arcuate conductors carry current in circumferentially opposite directions about said axis, and $2n$ spiral conductors of equal and constant pitch equiangularly disposed on the other of said faces coaxially of said axis, circumferentially adjacent of said spiral conductors being connected in series at radially similarly positioned ends thereof to form said spiral conductors into a two-terminal series winding, the pitch of said spiral conductors being substantially equal to $2n$ times said spacing, n being an integer.

22. A transformer comprising two insulating supports having each a plane face, means to support said supports with their said faces parallel to each other for relative rotation in an axis perpendicular to said faces, $2n$ spiral conductors of equal and constant pitch equiangularly disposed on one of said faces coaxially of said axis, circumferentially adjacent of said conductors being connected in series at radially similarly positioned ends thereof to form said conductors into a two-terminal series winding, and a conductor disposed on the other of said faces, said last-named conductor including a portion whose ends have as their points of nearest approach in the plane of said spiral conductors points differing in phase of the pitch cycle of any of said spiral conductors by a simple fraction of the pitch of any of said spiral conductors, n being an integer.

23. A transformer comprising two supports having each a plane face, means to support said supports with their faces parallel to each other for relative rotation in an axis perpendicular to said faces, a plurality of spiral conductors of equal and constant pitch disposed on one of said faces coaxially of said axis, each of said conductors being spaced from at least one other of said conductors by the same angular interval about said axis, circumferentially adjacent of said conductors being connected in series at radially similarly positioned ends thereof to form said conductors into a two-terminal series winding, and a conductor disposed on the other of said faces, said last-named conductor including a portion conforming to a circular arc coaxial with said axis and subtending at said axis an angle equal to a fraction of 360°.

24. A transformer comprising first and second insulating supports having each a plane face, means to support said supports with their said faces parallel to each other and with a substantially constant spacing therebetween for relative rotation in an axis perpendicular to said faces, $2n$ spiral conductors of equal and constant pitch equiangularly disposed on one of said faces coaxially of said axis, circumferentially adjacent of said conductors being connected in series at radially simi-

larly positioned ends thereof to form a two-terminal series winding, and two windings arranged on the other of said faces coaxially of said axis, said last-named windings extending circumferentially of said axis and having their centers of gravity separated by $360/4n$ degrees, n being an integer.

References Cited in the file of this patent

UNITED STATES PATENTS

1,134,840	Goldthorp	Apr. 6, 1915
1,610,122	Edenburg	Dec. 9, 1926
2,685,070	Childs	July 27, 1954

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 2,900,612 August 18, 1959

Robert W. Tripp

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 17, line 64, after "axis," insert -- each --.

Signed and sealed this 14th day of June 1960.

(SEAL)
Attest:

KARL H. AXLINE
Attesting Officer

ROBERT C. WATSON
Commissioner of Patents

UNITED STATES PATENT OFFICE

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