

Dec. 30, 1958

G. KRONACHER
MULTIPOLE PAIR RESOLVER

2,866,913

Filed June 27, 1956

3 Sheets-Sheet 1

FIG. 1

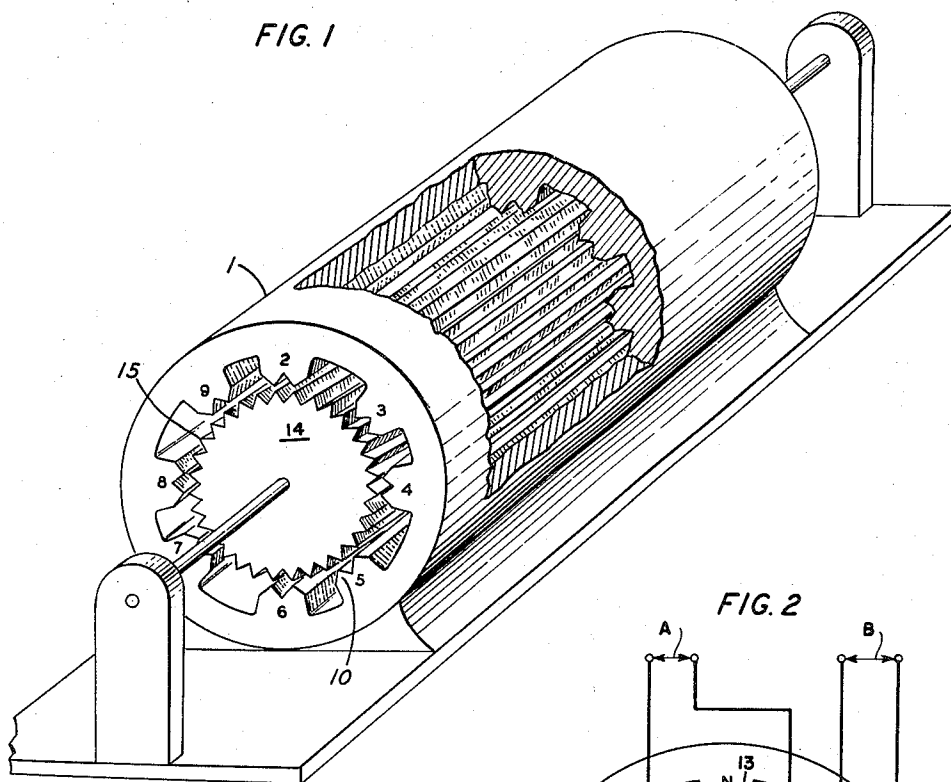


FIG. 2

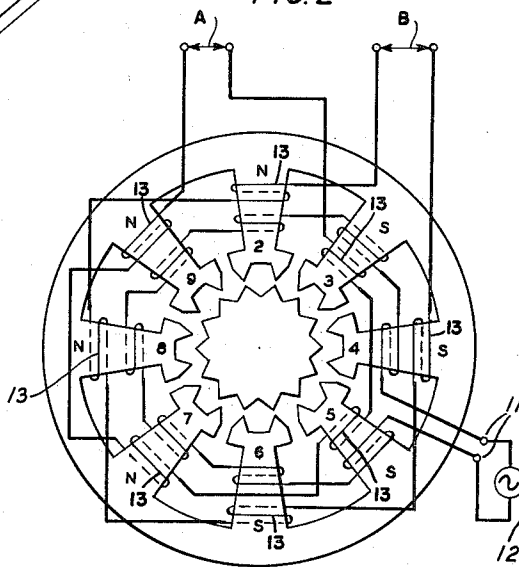
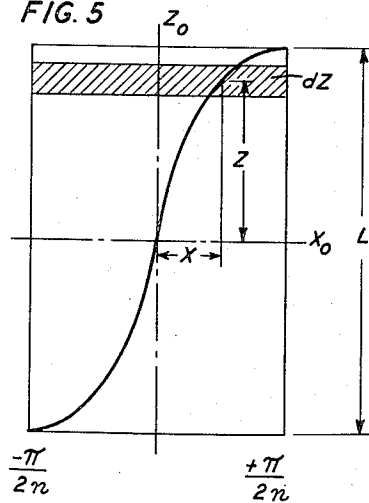


FIG. 5



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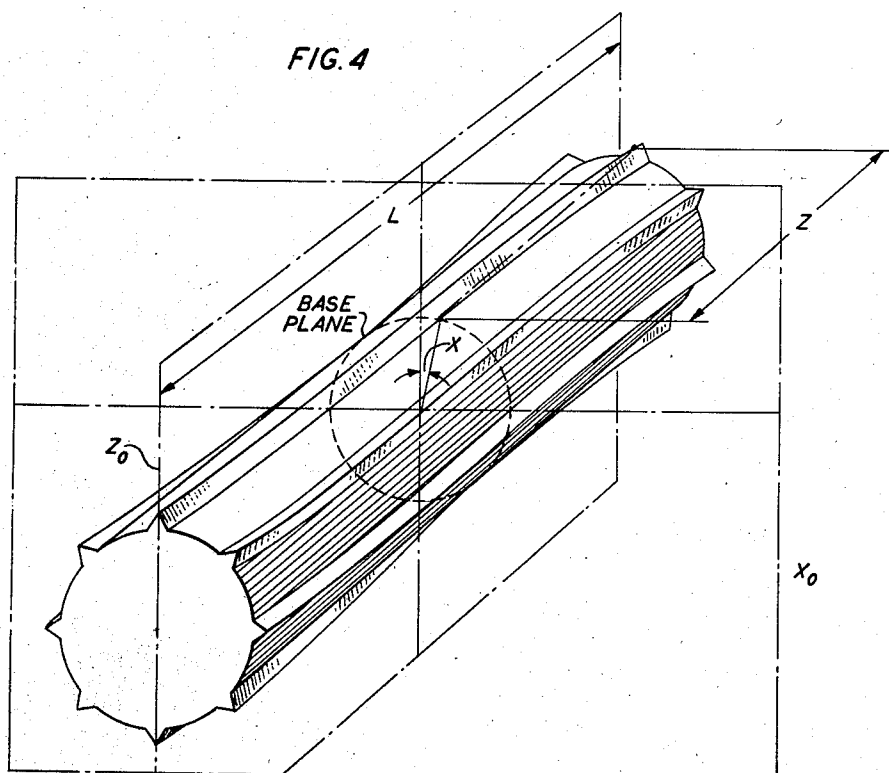
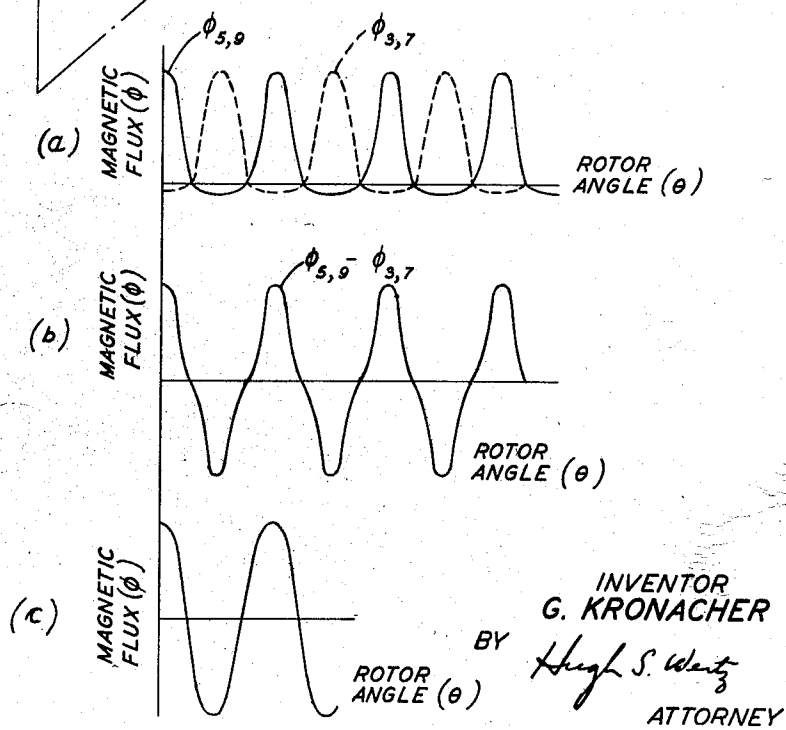


FIG 3



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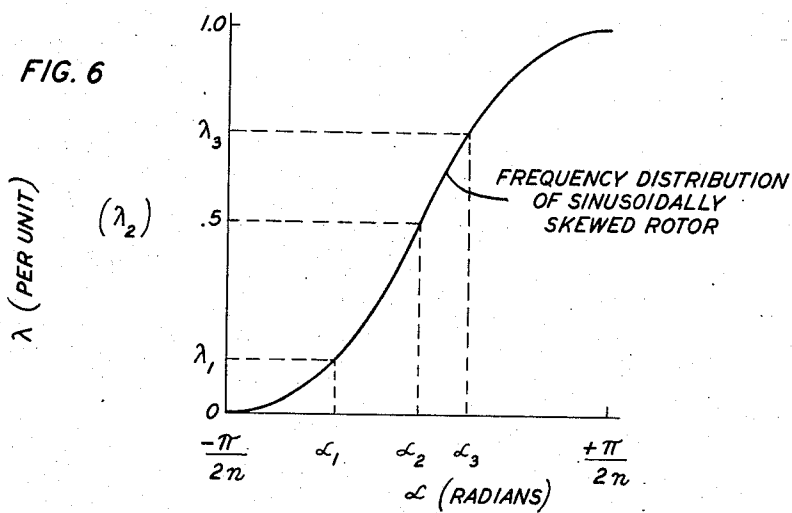
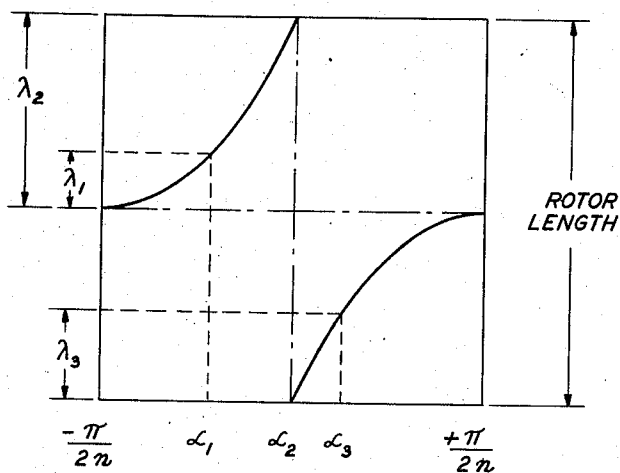


FIG. 7



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2,866,913

MULTIPOLE PAIR RESOLVER

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Application June 27, 1956, Serial No. 594,273

9 Claims. (Cl. 310—111)

This invention relates to electromagnetic devices having relatively movable members and, more particularly, to generators or resolvers for precision synchro systems which convert displacement, whether rotational or linear, into electrical signals.

Synchro devices are utilized for a variety of purposes including the production of electrical signals which are the analogs of desired information. As one application, an electrical synchro produces signals representative of the angular position of a shaft. It is well established that the angular position of a shaft may be represented by a sinusoid and for this reason it is convenient to have the synchro generate sinusoidally shaped signals with respect to the displacement of the shaft. It is apparent that any distortion in the analog signal reduces the accuracy of reproduction of the angular position. One of the principal distortions in the analog signal occurs when the mutual inductance between the windings varies with displacement of the shaft in a manner which is not precisely sinusoidal.

Although several methods may be employed to obtain a variable magnetic coupling between windings for electromagnetic devices having relatively movable members and utilizing transformer action for generating analog signals, only the two most widely used methods will be considered here. One method consists in mounting windings on both a stationary member and a controllably movable member of the device. This is the case in the resolver synchro devices, ordinary alternators, and similar devices having movable winding. The second method consists in mounting both windings on the stationary member and shaping the movable member so as to control the air gap permeance and thereby the flux path between the windings. The second method is employed in rotary reluctance devices such as high frequency alternators, inductor type frequency changers and similar devices requiring variable permeance characteristics.

From an electrical signal generation standpoint, with which we are concerned here, method 2 is the least complicated and most reliable since it eliminates the requirement of slip rings necessary to obtain the induced voltage from the rotor of a method 1 device. For this reason a synchro resolver of the precision here involved is best produced by a structure according to the second method.

A typical rotary reluctance device comprises a ferromagnetic stator provided with a plurality of pole shoes which have teeth parallel to the axis of the device. An excitation winding is wound on each shoe with the winding excited from a source of alternating current of suitable frequency. A second winding is located on each pole shoe and is mounted so as to be linked by the flux produced by the excitation winding, thereby providing an output signal for the device. The rotor of the device is a ferromagnetic cylinder mounted for rotation within the stator, and having a selected number of teeth on its surface. The mechanical rotation of the rotor causes the rotor and stator teeth to vary between a condition of alignment and one in which the teeth are effectively in mesh resulting in variation of the reluctance of the air gap

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under each pole shoe. Consequently, the flux linking the output winding varies according to the relative positions of the rotor and stator teeth.

It is well established that it is difficult to determine as well as to machine the tooth contour for either the rotor or stator teeth which will produce sinusoidal variation of the air gap permeance with respect to rotor rotation. In order to obtain sinusoidal variation of the pole shoe permeance with respect to the rotor angle, several techniques have been applied in the prior art. One technique involves the selection of the proper rotor and stator pitch. A second technique employed is choosing the proper crown width of the rotor teeth. Another practice involves skewing either the rotor or stator teeth with respect to one another. The usual rotor or stator has the teeth aligned with the axis of the electromagnetic device. The skewed rotor or stator has the teeth located on its surface in such a way that the angular displacement of the vertex of each tooth from a reference position varies as a function of the distance along the axis of rotation of the rotor. In the present designs of movable winding and reluctance type devices only linear skews are employed, that is, the locus of points on the surface of the rotor or stator as a result of such angular displacement of the tooth is a helix. Linear skews eliminate certain harmonic flux linkages which occur with rotor displacement but merely reduce the remaining harmonics.

It is the object of the present invention to increase the accuracy of conversion from analog information to electrical signals in a synchro resolver or a rotary reluctance device by the elimination of the odd harmonics in the flux linking the rotor and stator as relative rotation occurs.

In accordance with the present invention, a reluctance type resolver is provided with a stator core having an even number of pole shoes which are evenly divided between north and south poles. The pole shoes are arranged with equal numbers of teeth on each pole face and the shoes are equally spaced on the circumference of the stator. The stator core is wound with an excitation winding which is excited from a source of alternating current of desired frequency and the winding imparts to each pole shoe the same absolute value of magnetomotive force. A rotor is mounted for rotation within the stator about the axis of the resolver device. The rotor core is also arranged with a number of teeth equally spaced on its surface. The stator and rotor teeth are nonlinearly disposed with respect to each other. The nonlinear relationship between stator and rotor teeth may be described by a group of skews all of which have a frequency distribution (as defined for example in "Handbook of Probability and Statistics With Tables," by Burington and May Handbook Publishers, Inc., 1953, chapter III) of relative angular displacements the same as the frequency distribution of a sinusoidal curve. The most convenient skew, assuming an unskewed stator, is described for a rotor of length L and n teeth by the following equations in cylindrical coordinates:

$$Z = \frac{L}{2} \sin(nX) \quad (1)$$

$$r = R$$

r being the radial distance to the vertex of the rotor tooth cylinder of radius R ; X , the angle measured in the base plane from a reference; and Z the distance along the rotor axis measured perpendicularly from the base plane. For reasons which will become more apparent hereinafter, the base plane of the cylindrical coordinates is selected at the midpoint of the rotor axis. A similar relationship may be established for the stator but the rotor equation is chosen to facilitate the description of the device.

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The number of pole shoes and the number of rotor teeth are selected in such a way that the poles can be divided into two groups spaced an integral multiple of the pitch of the rotor teeth $\pm$ a quarter of this rotor tooth pitch. The pole shoes of a group are subdivided into a number of pairs whereby pole shoes of a pair are displaced from each other by an integral multiple of the rotor tooth pitch $\pm$ a half the rotor tooth pitch.

A sensing coil is located on each pole shoe and is wound in the same direction as the excitation winding. An output circuit includes the sensing coils of a group of pole shoes. The coils of a pole shoe pair are connected in opposition and the coil pairs of a pole shoe group are connected in series. Application of an alternating current to the excitation winding produces an alternating flux under each pole shoe. The amplitude of the flux is directly proportional to the permeance under the pole shoe. As the rotor is rotated through one full revolution, the amplitude of the pole shoe flux goes through n cycles (where n is the number of rotor teeth as defined above). Due to the effect of the nonlinear skew provided according to the invention, the permeance variations of a pole shoe pair contain on odd harmonics. The even harmonic permeance variation is cancelled out as a result of the connection in opposition of the sensing coils of the pair. The result is that the amplitude of the signal appearing in the output circuit varies truly sinusoidally as a function of rotor rotation. Because of the spatial displacement between the pole shoe groups, the amplitudes of the signals appearing in the output circuits are displaced from each other by one-quarter cycle or 90 degrees.

The above and other features of the invention will be described in the following detailed specification taken in connection with the drawings, in which:

Fig. 1 is an isometric drawing of a resolver according to the invention partially broken away to show the arrangement of the rotor and stator teeth;

Fig. 2 is an electrical circuit diagram of one embodiment showing a resolver which produces two sinusoidal voltages that are displaced one-quarter of a cycle;

Fig. 3 includes graphs of the induced voltage developed in an output circuit as a function of the rotor angle with curve (a) representing the voltage before interconnection of sensing coils for a rotor without skewed teeth; (b) represents the voltage after interconnection of sensing coils for a rotor without skewed teeth; and (c) represents the voltage after interconnection of sensing coils with a rotor having teeth skewed according to the sinusoidal distribution of the invention;

Fig. 4 is an isometric drawing of a suitable rotor for use in a synchro according to the invention but having only a limited number of teeth shown to facilitate the showing of the sinusoidally distributed skew; and the cylindrical coordinate system for describing the shape of the skew;

Fig. 5 is a graph of a sinusoidally skewed tooth placed on the developed rotor surface with the abscissa representing the angular displacement of a point on the tooth measured from a reference in a plane parallel to a first plane lying midway along the rotor axis; the ordinate indicating the axial displacement of the same point on the tooth from the intersection of the first plane and a second plane including the rotor axis and being normal to the first plane;

Fig. 6 is a frequency distribution of the rotor teeth angular rotation for a sinusoidally shaped skew; and

Fig. 7 is a graph of a nonlinear skew that produces the same effect on the odd harmonics of the air gap flux as a sinusoidal skew.

In Fig. 1 a resolver device is shown as comprising a stationary member or stator 1 having eight pole shoes (2 through 9) each with a plurality of inwardly projecting members or teeth 10. These pole shoes are equally spaced around the circumference of the stator. As shown in the electrical circuit of Fig. 2, the stator is provided

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with a single phase induction winding 11 of sufficient turns to develop predetermined magnetomotive forces of equal amounts at each pole shoe with pole shoes 3, 4, 5, 6 being wound to produce north poles for positive input currents and pole shoes 7, 8, 9, and 2 being wound to produce south poles for positive input currents. A source of alternating current 12 of desired frequency is connected across the terminals of winding 11.

A sensing coil 13 (see Fig. 2) is placed on each pole shoe, and is mounted in such a manner as to be linked with the magnetic field produced by winding 11. The coils 13 of pole shoes 3, 5, 7, and 9 are interconnected to form an output circuit A for the pole shoe group. The remaining coils 13, i. e., those on poles 2, 4, 6, and 8, are similarly interconnected to form a second output circuit B from the second pole shoe group. In the first group, sensing coils 13 on poles 3 and 7 are connected in series to form a first coil pair 3-7. Likewise, the sensing coils 13 on poles 5 and 9 are connected in series to form a second coil pair 5-9. The first and second coil pairs of the first group of poles are connected in opposition to produce an output which is the difference between the induced voltage for poles 3-7 and 5-9. In the second group of poles, sensing coils 13 on poles 2 and 6 are connected in series to form a first coil pair 2-6. Similarly, the sensing coils 13 on poles 4 and 8 are connected in series to form a second coil pair 4-8. The first and second coil pairs of the second group of poles are connected in opposition to produce an output which is the difference between the induced voltages for poles 2-6 and 4-8.

A rotor 14 is provided for the resolver and is mounted for rotation within the stator 11 by any of the well known methods employed in electrical machinery. The rotor mounting structure in Fig. 1 is schematic and is chosen only to permit a clear showing of the stator and rotor core structures. As shown, the rotor has a plurality of outwardly projecting members or teeth 15 equally spaced on its periphery.

It is apparent that as the rotor is rotated the stator and rotor teeth move between conditions of alignment and mesh. The number of stator and rotor teeth is selected so that the pole shoes of a group are spaced an integral multiple plus half a rotor pitch. Although the increment of rotor pitch may be either positive or negative, it may not be both in the same structure and is here taken as positive for convenience in exposition. A rotor pitch is defined as the circumferential distance between crown points of contiguous teeth. The second group of pole shoes has the same spacing as the first group of pole shoes but the group is spaced from the first group an integral multiple plus a quarter of a rotor pitch for reasons which will become more apparent hereinafter.

Referring to Fig. 2, it is evident that in the position shown the selected number of rotor and stator teeth results in alignment of teeth for poles 2 and 6 and meshing of the teeth for poles 4 and 8 both pole shoe pairs being in the first group of pole shoes. It is also evident that a similar relative spacing will exist between the stator and rotor teeth for the second group of pole shoes.

The flux produced by energizing the excitation winding 11 links the sensing coils 13 as it passes through the air gap and rotor structure of the device. For the first group of sensing coils on poles 3, 5, 7, and 9 shown on Fig. 3, the flux travels out from pole 3 which is of north polarity (as mentioned hereinbefore) and then through the air gap to rotor structure 4. Thence, it travels into pole 7 which is of south polarity (as mentioned hereinbefore) via the air gap and then through the stator frame to pole 3. A similar flux path may be described for poles 5-9. The reluctance or flux resistance in the flux path is proportional to the flux path length divided by the flux path area and the constant of proportionality is defined as reluctivity. The reluctivity for air is given a value of unity whereas that for the iron portion of the circuit

is lower and depends on the characteristics of the iron. The reluctance of the flux path is obtained by instantaneously summing the individual reluctances for the air gap and iron portions of a flux path. It is apparent that the interaction of the rotor and stator teeth causes the reluctance of the air gap and iron flux paths to pass through n variations for each full rotation of the rotor. A curve may be plotted of the flux variation under a pole shoe as a function of rotor angle and the curve will depend principally upon the shape of the stator and rotor teeth. Fig. 3(a) illustrates the flux versus rotor angle for pole pairs 3—7 and 5—9 which are spaced an integral multiple of the pitch of the rotor teeth plus half a rotor pitch. It will be recalled from Fig. 2 that one pole pair of a group comprises pole shoes with opposite polarities but having the same interaction of rotor and stator teeth. The other pole pair of the group also comprises pole shoes with opposite polarities and the same interaction of rotor and stator teeth, but where the interaction is inverted with respect to that of the first pole pair. Thus, the curve of flux variation for a pole group resembles a continuous series of sinusoidal half cycles. It should be noted, however, that the effect of the skew has not been considered in determining the curve of flux distribution.

It was previously stated that the sensing coils on a pole pair are linked by the flux produced by the pole pair and the coils are connected in series. The sensing coil pairs of a group of pole shoes are connected in opposition with the result that Fig. 3(b) indicates the induced voltage in an output circuit for the sensing coils of a pole group. The wave shape of the induced voltage is identical above and below the abscissa and well known wave analysis techniques indicate that in such cases the even harmonics of the flux variation with respect to rotor angle are eliminated.

However, the odd harmonics of the flux variation are present and it will now be shown that a sinusoidally distributed skew placed on the rotor surfaces according to the invention can eliminate the effects of these harmonics. The combined effect of connecting pole pairs of a group in opposition and the sinusoidal skew produces an output voltage that consists entirely of the fundamental of the flux variation in the air gap with respect to the rotor angle.

The shape of the skew in the preferred embodiment of the invention is in the form of a sinusoid. Fig. 4 indicates the rotor structure and teeth in more detail but for purposes of better illustration only a few of the teeth are shown. The skew is properly described with respect to a system of cylindrical coordinates wherein X_0 , the base plane, is taken normal to the rotor axis at its midpoint, this location being chosen for reasons which will become apparent hereinafter. Z_0 is a reference plane which includes the resolver's axis, and it is normal to the X_0 plane. The curves made by the rotor teeth are functions of r the radius of the cylinder contiguous to the vertex of the rotor teeth; X the angular displacement from a reference of points on a tooth measured in a plane parallel to the base plane X_0 ; and Z the distance in the Z_0 plane of corresponding points from the intersection of the X_0 and Z_0 planes. Since the radius of the rotor teeth cylinder is constant, the sinusoidal skew may be accurately described as functions of the Z and X parameters, and Equation 1 previously given defines the preferred skew with respect to the cylindrical coordinate system shown in Fig. 4. The flux variation under pole shoes 3—7 and 5—9, as shown in Fig. 3(b), describes a cosine function of $(n\theta)$ since the flux passes through n cycles for a rotor angle θ of 2π radians. θ is the angular rotation imparted to the rotor 14 from an outside source whereas X is the structural displacement of points on a rotor tooth from a reference. Without rotor rotation the described embodiment would be no more than a 75

transformer. A Fourier series may be written for the flux variation as follows:

$$\phi = \sum_{\mu=1,3,5,\dots}^{\infty} A_{\mu} \cos(n\theta) + A_3 \cos(3n\theta) + \dots + A_{\mu} \cos(\mu n\theta) + \dots \quad (2)$$

In the Fourier series, A_{μ} represents the maximum amplitude of a harmonic of order μ . Since all harmonics in the flux variation are odd, they are described by the following relation where m is any positive integer:

$$\mu = 2m - 1 \quad (3)$$

The magnitude of the flux per unit length of the rotor for an unskewed rotor is Equation 2 divided by the rotor length:

$$\phi \text{ per unit} = \sum_{\mu=1,3,\dots}^{\infty} \frac{A_{\mu} \cos(\mu n\theta)}{L} \quad (4)$$

For a rotor with skewed teeth, as shown in Fig. 5, the distribution of flux along the rotor is changed by the skewed teeth. The magnitude of the flux per unit rotor length axial distance Z from the rotor center is:

$$\phi \text{ skewed per unit} = \sum_{\mu=1,3,\dots}^{\infty} \frac{A_{\mu} \cos \mu n(\theta+x)}{L} \quad (5)$$

The total flux of pole shoes 3—7 and 5—9 is obtained by integrating Equation 5 over the rotor length L :

$$\phi \text{ skewed} = \sum_{\mu=1,3,\dots}^{\infty} \int_{-\frac{\pi}{2n}}^{+\frac{\pi}{2n}} \frac{A_{\mu} \cos \mu n(\theta+x)}{L} dZ \quad (6)$$

The value of dZ may be found in terms of x to permit integration of Equation 4 by differentiating Equation 1 and substituting into Equation 4 as follows:

$$\phi \text{ skewed} = \frac{nA_{\mu}}{2} \sum_{\mu=1,3,\dots}^{\infty} \int_{-\frac{\pi}{2n}}^{+\frac{\pi}{2n}} \cos \mu n(\theta+x) \cdot \cos(nx) dx \quad (7)$$

$$\cos \mu n(\theta+x) = \cos \mu n\theta \cos \mu nx - \sin \mu n\theta \sin \mu nx$$

$$\phi \text{ skewed} = \frac{nA_{\mu}}{2} \sum_{\mu=1,3,\dots}^{\infty} \int_{-\frac{\pi}{2n}}^{+\frac{\pi}{2n}} \cos \mu n\theta [\cos(\mu nx) \cos(nx)] dx - \quad (8)$$

$$\int_{-\frac{\pi}{2n}}^{+\frac{\pi}{2n}} \sin \mu n\theta [\sin(\mu nx) \cos(nx)] dx \quad (9)$$

$$\cos(\mu nx) \cos(nx) = \frac{1}{2} [\cos(\mu+1)nx + \cos(\mu-1)nx] \quad (10)$$

$$\sin(\mu nx) \cos(nx) = \frac{1}{2} [\sin(\mu+1)nx + \sin(\mu-1)nx] \quad (11)$$

$$\phi \text{ skewed} = \frac{nA_{\mu}}{4} \sum_{\mu=1,3,\dots}^{\infty} \int_{-\frac{\pi}{2n}}^{+\frac{\pi}{2n}} \cos(\mu n\theta) [\cos(\mu+1)nx + \cos(\mu-1)nx] dx - \quad (12)$$

$$\int_{-\frac{\pi}{2n}}^{+\frac{\pi}{2n}} \sin \mu n\theta [\sin(\mu+1)nx + \sin(\mu-1)nx] dx$$

The magnitude of third harmonic flux of the Fourier series is found by letting $\mu=3$, and substituting into Equation 12

$$\phi_3 = \frac{nA_3}{4} \int_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} \cos 3n\theta [\cos 4nx + \cos 2nx] dx - \frac{nA_3}{4} \int_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} \sin 3n\theta [\sin 4nx + \sin 2nx] dx \quad (13)$$

$$\phi_3 = \frac{nA_3}{4} \cos 3n\theta \left[\frac{1}{4n} \sin 4nx + \frac{1}{2n} \sin 2nx \right] \int_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} dx - \frac{nA_3}{4} \sin 3n\theta \left[-\frac{1}{4n} \cos 4nx - \frac{1}{2n} \cos 2nx \right] \int_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} dx \quad (14)$$

$$\phi_3 = \frac{nA_3}{4} \cos 3n\theta \left[\frac{1}{4n} \sin 2\pi + \frac{1}{2n} \sin \pi - \frac{1}{4n} \sin (-2\pi) - \frac{1}{2n} \sin (-\pi) \right] + \frac{nA_3}{4} \sin 3n\theta \left[\frac{1}{4n} \cos 2\pi + \frac{1}{2n} \cos \pi - \frac{1}{4n} \cos (-2\pi) - \frac{1}{2n} \cos (-\pi) \right] \quad (15)$$

The bracketed expressions in Equation 15 reduce to zero since there is no difference between the angular quantities. Thus, the third harmonic flux is zero. It may be readily established that substitution of all odd harmonics except the fundamental reduces Equation 15 to zero. The magnitude of the fundamental of the Fourier series is found by letting $\mu=1$ and substituting into Equation 12

$$\phi_1 = \frac{nA_1}{4} \int_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} \cos n\theta (\cos 2nx + \cos 0) dx - \frac{nA_1}{4} \int_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} \sin n\theta (\sin 2nx + \sin 0) dx \quad (16)$$

$$\phi_1 = \frac{nA_1}{4} \cos n\theta \left[\frac{1}{2n} \sin 2nx + x \right]_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} - \sin n\theta \left[-\frac{1}{2n} \cos 2nx \right]_{-\frac{\pi}{2n}}^{\frac{\pi}{2n}} \quad (17)$$

$$\phi_1 = \frac{nA_1}{4} \cos n\theta \left[\frac{1}{2n} \sin \pi + \frac{\pi}{2n} - \frac{1}{2n} \sin (-\pi) + \frac{\pi}{2n} \right] + \sin n\theta \left[\frac{1}{2n} \cos \pi - \frac{1}{2n} \cos (-\pi) \right] \quad (18)$$

$$\phi_1 = \frac{nA_1}{4} \cos n\theta \frac{\pi}{n} + 0 \quad (19)$$

$$\phi_1 = \frac{\pi A_1}{4} \cos n\theta \quad (20)$$

Equation 12 indicates that the magnitude of the flux, under pole shoe pairs 3—7, 5—9 as a result of sinusoidally skewing the rotor will vary sinusoidally as a function of rotor rotation.

Since the variation of air gap flux under each pole shoe pair is sinusoidal with rotor rotation then Fig. 4(c) indicates the air gap flux variation for a pole group with the effect of the sinusoidal skew taken into consideration. It will be recalled that the resolver has two pole groups which are displaced from each other by an integral multiple plus a quarter of a rotor pitch. It may be shown by similar mathematical procedures that the flux variation for the second pole shoe group is sinusoidal but due to the spatial displacement between the groups there is a quarter cycle variation or 90 degrees between the flux linking the coil groups.

There are other nonlinear skews which will eliminate generation of odd harmonics in the air gap flux from the movement of the rotor. If the sinusoidally skewed rotor is considered as comprising an infinite number of laminations, then the summation of the flux associated with each lamination is without odd harmonics as the rotor turns through an angle equal to that subtended by the tooth pitch. It will be recognized that rearranging the axial occurrence of each lamination but preserving the angular orientations of each will not alter the summation of the flux as found for a sinusoidally skewed rotor. In addition, the frequency distribution of the angular displacements for the rearranged rotor laminations is the same as the frequency distribution of angular displacements for a sinusoidally skewed rotor. A frequency distribution is here represented by a graph in which the abscissa is angular displacement and the ordinate for a particular abscissa is the portion of the total rotor length for which the indicated angular displacement of the teeth with respect to a reference as previously defined exceeds a minimum displacement but is less than the displacement indicated for that abscissa. Hence, there are an infinite number of nonlinear skews which may be employed to eliminate odd harmonics in the air gap flux since each rearrangement of the order of occurrence of laminations of particular angular displacements is a possible nonlinear skew. However, all nonlinear skews have the same frequency distribution of angular displacement as a sinusoidal skew.

In Fig. 5, the maximum angular displacement of a rotor tooth is shown as

$$+\frac{\pi}{2n}$$

and the minimum angular displacement is shown as

$$-\frac{\pi}{2n}$$

If $\lambda(-\pi/2n, \alpha)$ is the portion of the total rotor length rotationally displaced more than

$$-\frac{\pi}{2n}$$

and less than α with respect to the median displacement (median being maximum angular displacement + minimum angular displacement $\div$ two) and α is the angular displacement of a given lamination with respect to the median, then the resultant curve is the frequency distribution of angular displacement for a sinusoidal skew. In Fig. 6 the frequency distribution curve for a sinusoidal skew is shown and the equation for the curve is as follows:

$$\lambda(-\pi/2n, \alpha) = \frac{1}{2} \sin n\alpha + \frac{1}{2} \quad (21)$$

It will be recalled that n is the number of rotor teeth on the rotor surface.

In Fig. 7, a nonlinear skew is shown which appears quite different from a sinusoidal skew. The frequency distribution of angular displacement for the skew is obtained by arbitrarily selecting the various α 's and determining the λ 's associated with each α . For α_1 the magnitude of λ_1 represents the portion of the total rotor length angularly displaced more than $-\pi/2n$ and less than α_1 with respect to the median displacement. Likewise, λ_2 represents the portion of the total rotor length angularly displaced for α_2 . For α_3 the portion of the total rotor length angularly displaced is given by $\lambda_2 + \lambda_3$ since each lamination is rotated more than $-\pi/2n$ but less than α_3 . A plot of the λ 's against the α 's for Fig. 7 is shown on Fig. 6 and it is evident that the equation of the curve is same as that for Fig. 6. Hence, the skew shown in Fig. 7 will eliminate odd harmonics in the air gap flux as the rotor turns.

The operation of the resolver occurs when the excitation winding is energized from source 12, and rotor 14 is rotated. As the rotor rotates the air gap flux which links sensing coils 13 is caused to vary as a result of the interaction of the stator and rotor teeth. It should be understood that the rotor-stator teeth flux variation is superimposed on the time variation of the flux which originates from the source of alternating current 12. The nonlinear skew having a frequency distribution curve the same as Equation 21 eliminates odd harmonics in the air gap flux as the rotor turns through an angle equal to that subtended by the tooth pitch. The even harmonics in the air gap flux as the rotor turns are cancelled out as a result of the connection of sensing coils 13 for a pole pair in opposition. The voltage appearing in each output circuit is a modulated carrier of the frequency provided by source 12, and the envelope of the carrier is without odd or even harmonics. The output voltage may therefore be employed very precisely to represent the angular position of the rotor.

It is to be understood that the invention has been described in connection with specific embodiments, and other modifications and embodiments will readily occur to one skilled in the art without departing from the spirit of the invention.

What is claimed is:

1. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having a plurality of teeth equally spaced about its periphery, the angular positions of points on an individual tooth as measured from the reference formed by the intersection of a plane including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth, being a sinusoidal function of the distance along the rotor measured parallel to said axis, at least a pair of poles formed on said stator and having teeth parallel to said axis, said poles being spaced an integral multiple plus half a rotor tooth pitch, means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, and means inductively coupled to said flux pattern to provide an output free of even harmonics as the rotor turns.

2. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having a plurality of teeth equally spaced about its periphery the angular positions of points on an individual tooth, as measured from the reference formed by the intersection of a plane including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth, being a sinusoidal function of the distance along the rotor measured parallel to said axis, at least two pairs of poles formed on said stator and having teeth parallel to said axis, the poles of each pair being spaced an integral multiple plus half a rotor tooth pitch and the angular separation between poles of different groups being an integral multiple plus one-quarter rotor tooth pitch,

means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, and means inductively coupled to said flux pattern to provide an output free of even harmonics as the rotor turns.

3. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having a plurality of teeth equally spaced about its periphery the angular positions of points in an individual tooth, as measured from the reference formed by the intersection of a plane including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth, being a sinusoidal function of the distance along the rotor measured parallel to said axis, at least a pair of poles formed on said stator and having teeth parallel to said axis, said poles being spaced an integral multiple plus half a rotor tooth pitch, means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, a sensing coil mounted on each of said poles for inductive coupling to said flux pattern, and means serially interconnecting said coils to provide an output proportional to the difference of the voltages induced therein.

4. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having a plurality of teeth equally spaced about its periphery the angular positions of points in an individual tooth, as measured from the reference formed by the intersection of a plane including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth, being a sinusoidal function of the distance along the rotor measured parallel to said axis, at least a pair of poles formed on said stator and having teeth parallel to said axis, said poles being spaced an integral multiple plus half a rotor tooth pitch, means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, a sensing coil mounted on each of said poles for inductive coupling to said flux pattern, and means serially interconnecting the coils of each of said paired poles to provide individual outputs proportional to the difference of the voltages induced therein.

5. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having n teeth equally spaced about its periphery, the angular positions of points on an individual tooth as measured from the reference formed by the intersection of a plane Z_0 including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth being defined by the expression

$$Z = \frac{L}{2} \sin n\alpha$$

where Z is the distance along the rotor measured parallel to said rotor axis from a reference plane X_0 normal to said rotor axis at its midpoint and L is the total length of said rotor, at least a pair of poles formed on said stator and having teeth parallel to said axis, said poles being spaced an integral multiple plus half a rotor tooth pitch, means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, and means inductively coupled to said flux pattern to provide an output free of even harmonics.

6. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having n teeth equally spaced about its periphery, the distribution of angular displacement of elements on a rotor tooth vertex the same as a sinusoid, at least a pair of poles formed on said stator and having teeth parallel to the said axis, said poles being spaced an integral multiple plus half a rotor tooth pitch, means for establishing a single phase sinusoidal

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flux pattern in said stator, means for imparting mechanical rotation to said rotor, and means inductively coupled to said flux pattern to provide an output.

7. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having n teeth equally spaced about its periphery, the distribution of angular displacements of elements on a rotor tooth vertex being defined by $\lambda = \frac{1}{2} \sin n\alpha + \frac{1}{2}$ where λ equals the portion of the total rotor length for which the angular displacements of the rotor tooth vertices are more than

$$\frac{\pi}{2n}$$

and less than α measured from a reference formed by the intersection of a plane including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth, at least a pair of poles formed on said stator and having teeth parallel to said axis, said poles being spaced an integral multiple plus half a rotor tooth pitch, means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, and means inductively coupled to said flux pattern to provide an output.

8. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having n teeth equally spaced about its periphery, the distribution of angular displacements of elements on a rotor tooth vertex being defined by $\lambda = \frac{1}{2} \sin n\alpha + \frac{1}{2}$ where λ equals the portion of the total rotor length for which the angular displacements of the rotor tooth vertices are more than

$$\frac{\pi}{2n}$$

and less than α measured from a reference formed by the intersection of a plane including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth, at least a pair of poles formed on said

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stator and having teeth parallel to said axis, said poles being spaced an integral multiple plus half a rotor tooth pitch, means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, and means inductively coupled to said flux pattern to provide an output free of even harmonics.

9. In an electromagnetic device for generating substantially pure sinusoidal voltages a stator, a rotor mounted for rotation therein, said rotor having a plurality of teeth equally spaced about its periphery, the distribution of angular displacements of elements on a rotor tooth vertex being defined by $\lambda = \frac{1}{2} \sin n\alpha + \frac{1}{2}$ where λ equals the portion of the total rotor length for which the angular displacements of the rotor tooth vertices are more than

$$\frac{\pi}{2n}$$

and less than α measured from a reference formed by the intersection of a plane including the rotor axis and a cylinder having the same axis and tangent to the vertices of said rotor teeth, at least two pair of poles formed on said stator and having teeth parallel to said axis, the poles of each pair being spaced an integral multiple plus half a rotor tooth pitch and the angular separation between poles of different groups being an integral multiple plus one-quarter rotor tooth pitch, means for establishing a single phase sinusoidal flux pattern in said stator, means for imparting mechanical rotation to said rotor, a sensing coil mounted on each of said poles for inductive coupling to said flux pattern, and means serially interconnecting the coils of each of said paired poles to provide individual outputs proportional to the difference of the voltages induced therein.

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