July 10, 1945.

B. V. HOARD

2,379,905

HIGH SPEED RELAY

Filed Sept. 1, 1942

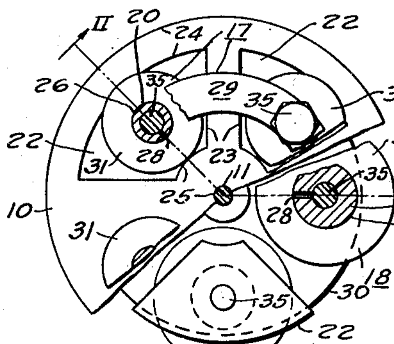

Fig. 1.

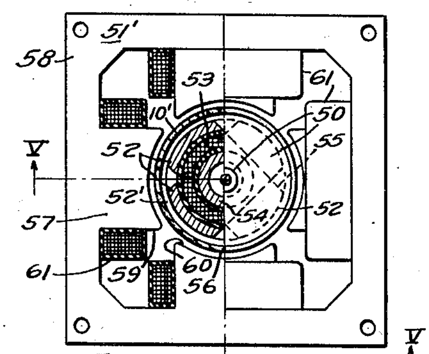

Fig. 4.

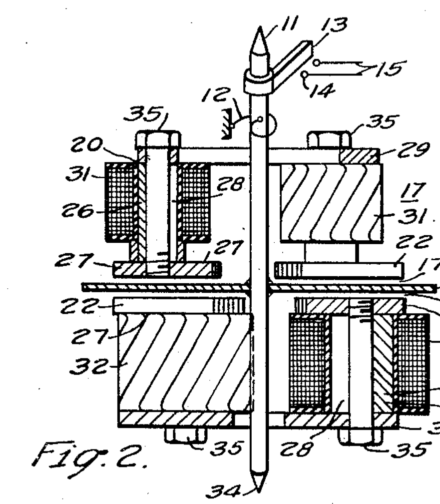

Fig. 2.

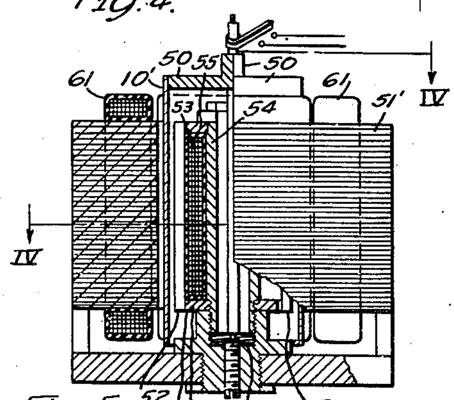

Fig. 5.

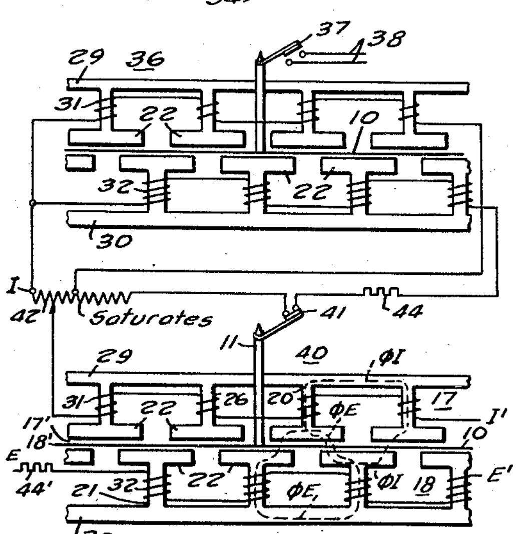

Fig. 3.

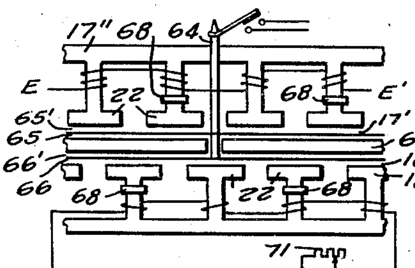

Fig. 6.

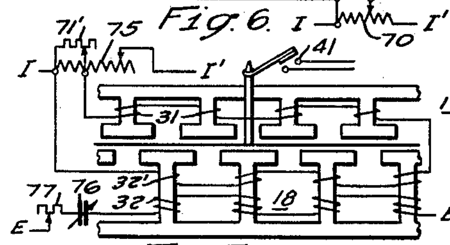

Fig. 7.

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HIGH-SPEED RELAY

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Application September 1, 1942, Serial No. 456,901

23 Claims. (Cl. 175—294)

My invention relates to high-speed alternating-current relays such as are used in the protection of electrical transmission systems, and for other purposes.

An object of my invention is to provide a new type of induction-disk or induction-cylinder relay in which practically all of the available surface of the induction-element is covered, with airgap-separation, by the pole faces of a magnetic stator-structure which extends substantially all the way around a complete circle. By means of my new construction, or principles of construction, I am enabled to obtain many important advantages, including higher speed, a larger ratio of useful torque to rotor-inertia, increased sensitivity, low space-requirements, comparative freedom from stray-current torques or unwanted torques of any kind, increased range of low-voltage operation, a saturated iron magnetic circuit for the current-responsive torque, freedom from vibration and rattle, uniform torque at all positions of the relay, freedom of interference from stray fields, ease of inspection with respect to dirt, substantial reduction in the sensitivity to the direct-current component of asymmetrical fault-currents, insensitivity to mechanical shocks, insensitivity to dirt, better calibration-characteristics, greater ease of construction and adjustment, and, in some cases, the possibility of utilizing a single current-coil.

A further object of my invention is to provide a novel construction, and a novel principle of operation, of a reactance-type relay, which may be either a resistance-responsive relay, a reactance-responsive relay, or a modified-reactance relay which responds to both the line-reactance and the line-resistance, in any desired proportions.

With the foregoing and other objects in view, my invention consists in the structures, mechanisms, combinations, parts, systems, and methods, hereinafter described and claimed, and illustrated in the accompanying drawing, wherein:

Figure 1 is a plan view of a high-speed induction-disk relay embodying certain features of my invention in the form of a directional or wattmeter element with separate magnetic circuits for the current-responsive flux and the voltage-responsive flux, parts being broken away to illustrate the construction;

Fig. 2 is a vertical sectional view on the plane indicated by the line II—II in Fig. 1;

Fig. 3 is a diagrammatic development-view showing the multipolar construction spread out in a straight line, illustrating the magnetic flux-paths, and also illustrating the electrical connections for an embodiment of two of my disk-type relay-elements in a directionally controlled overcurrent relay;

Fig. 4 is a plan view, partly in horizontal section on the plane indicated by the line IV—IV in Fig. 5, illustrating an embodiment of my invention in an induction-cylinder type;

Fig. 5 is an elevational view of the same cylinder-type relay, partly in section on the plane indicated by the line V—V in Fig. 4; and

Figs. 6 and 7 are diagrammatic views, similar to Fig. 3, illustrating applications of my invention to an impedance-relay and a reactance-relay, respectively.

In Figs. 1 and 2, I show my invention as being embodied in an alternating-current electroresponsive relay, specifically a wattmeter or directional element, utilizing a light-weight, rotatably mounted torque-producing member 10 which is mounted at right angles on a rotatable shaft 11 which is restrained by a spring 12 (Fig. 2), and which carries a movable contact-member 13 which is adapted to cooperate with stationary contacts 14 of a relay-controlled circuit 15. The essential feature of the torque-producing rotor-member 10 is that it shall comprise a continuous, sheet-like, light-weight, and usually preferably non-magnetizable, conducting-portion having a surface which returns circularly on itself. In Figs. 1 and 2, this torque-producing rotor-member is shown in the form of a disk 10. In Figs. 4 and 5, it is shown in the form of a hollow cylinder 10′.

Cooperating with the rotor-disk 10, in the apparatus shown in Figs. 1 and 2, is a stator-member comprising two magnetizable multipolar flux-producing means 17 and 18, disposed one above the rotor-member 10 (the shaft being vertical), and the other below said rotor-member, with airgaps 17′ and 18′ in between. Each of the multipolar flux-producing means 17 and 18 extends substantially all the way around the circularly continuous surface of the rotor-disk 10 or other sheet-like conducting-portion which constitutes the torque-producing member of my device. By the term "multipolar," I mean a construction having more than one pole, and specifically, a construction having an even number of north and south poles, so that the term will embrace a construction using either two, four, six, or more, poles on each side of the disk. In the particular form of embodiment shown in Fig. 1, there are four poles 20 and 21, respectively, on each side of the disk 10. The poles 20 of the stator-structure 17 above the disk 10 are displaced in something like a quadrature space-relation with respect to the poles 21 of the stator-structure 18 beneath the disk 10.

I utilize a novel form of construction for each of the multipolar structures 17 and 18 of my invention. As shown in Figs. 1, 2 and 3, each of the pole-pieces 20 or 21 has a magnetizable, flat, pole-face member 22 having its front face presented to the airgap 17′ or 18′, as the case may be. In the induction-disk form of construction shown in Figs. 1 and 2, each pole-face member **22** has a substantially segmental or sector shape, as clearly shown in Fig. 1, so that all four of the pole-face members of each of the magnet structures **17** and **18** will extend all the way around the circumference of the disk, with certain spacings **23** between the radial edges of adjacent sector-shaped pole-face members **22**, spacings **24** between the outer periphery of each pole-face member **22** and the outer periphery of the disk **10**, and spacings **25** between the inner peripheries of the pole-face members **22** and the shaft **11**. These spacings **23**, **24** and **25** constitute portions or areas of the disk **10** which are not covered (through the airgap) by the pole-face members **22**, and it will be noted that each pole-face member **22** is entirely surrounded by an uncovered portion or area of the disk **10**, as represented by said spacings **23**, **24** and **25**, thus providing a path for eddy-currents which are induced in the disk by the alternating magnetic flux in the respective pole-face portions **22**.

Each pole-piece comprises, in addition to the pole-face portion **22**, a magnetizable pole-shank portion **26** which extends back from a small portion of the back face **27** of the pole-face member **22**, extending away from the airgap. In the disk-type relay shown in Figs. 1 and 2, these pole-shank portions extend in directions parallel to the shaft **11**. An advantage of this form of construction is that the pole-shank portions **26** may be in the form of iron or steel tubes, which may be split, as indicated at **28**, to reduce eddy-current losses in the magnetic circuit, thus avoiding the need for a laminated construction.

Each of the magnetic stator-structures **17** and **18**, in Figs. 1 and 2, is completed by means of a magnetizable yoke-member shown at **29** and **30**, respectively. These yoke-members join the rear ends of the shanks **26** of the pole-pieces of different polarities, thus providing a return-flux path. Each of the pole-shank portions **26** is surrounded by a magnetizing coil **31** or **32**, the coils **31** of the upper magnetic structure **17** being preferably the current-responsive coils, while the coils **32** of the lower magnetic structure **18** are preferably the voltage-responsive coils, the current-responsive coils being put on top, so that, under fault-conditions, when the current is excessive, the pulsatory repulsion existing between the current-energized pole-pieces and the induction disk will press the disk more firmly down against the lower thrust-bearings, which support the weight of the rotor-member at **34**, thus avoiding lifting the rotor-member and causing chattering at this thrust-bearing. The respective multipolar structures **17** and **18** may be conveniently assembled by means of either magnetizable or non-magnetizable bolts **35** extending through the several pole-shank portions **26**.

In Fig. 3, I have shown two of my induction-disk structures, similar to that shown in Fig. 1, in a diagrammatic developed view in which the circumference of the disk is opened up and spread out in a straight line to show the circumferential magnetic flux-paths. In Fig. 3, the upper relay-element **36** is an overcurrent relay having its contacts **37** in the relay-controlled circuit **38**, while the lower relay-element **40** is a directional or wattmeter type of element, having its contacts **41** in series with an energizing-circuit of the overcurrent relay **36**, so that the overcurrent element may be energized or deenergized in response to the direction of current-flow, as determined by the directional element **40**.

In Fig. 3, the line-current is delivered to the current-coil circuit **31** of the lower or directional element **40**, through the terminals I, I′, in a circuit which includes an autotransformer **42** which supplies current both to the current-coils **31** and the voltage-type coils **32** of the upper, or overcurrent, element **36**. The current which is supplied to the voltage-type coils **32** of the overcurrent element **36** is at a smaller current-value and a high voltage-value than the current supplied to the current-coils **31** of the same element **36**, and the relative phases of the exciting-currents in the current and voltage-windings **31** and **32** of this overcurrent element **36** are controlled so that the two fluxes will be displaced, usually about 45° with respect to each other. To this end, I have shown a resistance **44** in series with the voltage-type coils **32** of the overcurrent element **36**.

In Fig. 3, the line-voltage is supplied to the voltage-coils **32** of the directional element **40**, from the terminals E, E′, a resistance **44′** being again added to control the phase-relationships, to the end that maximum relay torque will occur when the current in the current-coils **31** of the relay lags the impressed voltage across the relay by approximately 45°, so that the directional-relay connection known as the 90° connection may be used.

Reference to Fig. 3 will show that the current-responsive flux ϕI which flows up in one pole-shank and down in the next adjacent pole-shank of the upper magnetic structure **17** of each relay-element, such as the directional element **40**, crosses both airgaps **17′** and **18′**, and completes its circuit by a circumferential traversal of one of the pole-face portions **22** of the lower magnetic structure **18**, the ϕI magnetic flux-path being completed through the yoke-member **29** of the upper magnetizable structure **17**. In like manner, the magnetic circuit of the voltage-responsive flux ϕE is completed by a circumferential traversal of one of the pole-face portions **22** of the upper magnetic structure **17**, after the flux has traversed both airgaps **17′** and **18′** two times, including also two passages through the thickness of the disk **10** as in the case of the flux ϕI. The current-responsive magnetic flux ϕI of the upper structure **17** does not traverse any part of the lower structure **18** other than the pole-face portions **22** thereof, and, similarly, the voltage-responsive flux ϕE of the lower structure **18** does not traverse any part of the upper structure **17** other than the pole-face portions **22**. These pole-face portions **22** are designed with sufficiently liberal cross-sectional areas, with respect to fluxes flowing in a circumferential direction therein, so as to avoid saturation, as far as possible, and to provide a ready return-flux path for the flux which comes from the other magnetic stator-structure **18** or **17**, as the case may be.

It is frequently desirable to deliberately provide for saturation of the magnetic flux-path for the current-responsive flux ϕI; and it is one of the desirable features of my invention that this may be readily accomplished, by reason of the fact that the magnetic path for the current-responsive flux ϕI is quite independent of the magnetic path for the voltage-responsive flux ϕE, except for the respective pole-face portions **22**. Such a saturation of the magnetic path for the current-responsive flux ϕI is quite desirable, in order to protect the relay from the overheating effects of excessive line-currents, and the bounce-producing effects of the excessive pulsating torques when the line-current is high, as under fault-conditions. In my structure, the saturation of the current-responsive flux-path may be readily accomplished by making the shank-portions **26** and/or the magnetic yoke portions **29** of the current-responsive magnetic structure of a sufficiently reduced cross-section, as shown in Figs. 1, 2 and 3. To the same end, it is usually desirable to design the autotransformer **42**, of Fig. 3, so that it will saturate, thus protecting the upper, or overcurrent, element **36** against excessive current-values.

A double operating-torque is produced in the disk **10**, or other continuous, sheet-like conducting-portion which constitutes the torque-producing member of my device. It will be noted, from Fig. 3, that the thickness of the disk **10** is crossed by two different flux-paths, one of them coming from the current-responsive magnetic structure **17**, and the other coming from the voltage-responsive magnetic structure **18**; and each of these flux-paths is an alternating flux, producing eddy-currents in the portions of the disk surrounding the respective segmental-shaped pole-faced members **22** of both the upper and lower field structures **17** and **18**. The current-responsive eddy-currents in the disk **10** cooperate with the voltage-responsive flux ϕE to produce a torque proportional to the product of the current times the voltage times a function of the angle between the two fluxes ϕI and ϕE. In like manner, the voltage-responsive eddy-currents in the disk **10** cooperate with the current-responsive flux ϕI to produce a torque proportional to the product of the current times the voltage times a function of the angle between the two fluxes ϕI and ϕE. These two torques combine to produce a strong operating-force or torque in a small space.

Reference to Fig. 1 will show that every possible square inch of surface of the disk **10**, both top and bottom, is utilized to produce as much torque as possible, by the reactions between the eddy-currents in the disk and the respective fluxes in the upper and lower magnetic structures **17** and **18**. It will be noted that the segmental-shaped pole-face portions **22** of both the upper magnetic structure **17** and the lower magnetic structure **18** substantially cover almost the entire face of the disk **10**, being separated therefrom by only a short or narrow airgap **17′** or **18′**, as the case may be. I say "almost" because it is quite important not to cover the entire surface of the disk with the projected areas of the pole-face portions **22**, but to leave the previously described spaces **23**, **24** and **25** of Fig. 1, to provide portions of the disk **10** in which the induced eddy-currents may completely encircle each of the pole-face portions **22**. Tests have shown that the available torque is considerably reduced if these spaces **23**, **24** and **25** are made either too small or too large, meaning that either there is too much leakage-flux between poles and too little useful flux through the disk, or that the disk-inertia will be increased faster than the useful flux, or the torque resulting is decreased speed. In a disk of 3¼ inches diameter, spacings of the order of ¼ inch are satisfactory for the spacings **23**, **24** and **25** in Fig. 1.

My disk-type construction, as shown in Figs. 1, 2 and 3, has many advantages over other types of high-speed alternating-current relays known in the art. Important advantages include the provision of substantially separate flux-paths for the current-induced flux and the voltage-induced flux, thus largely minimizing stray-flux effects which have proven quite critical, and quite harmful to the sensitivity of many previous relays. The fact that the torque produced in my relay is substantially independent of the position of the moving element of the relay, or of the degree of separation or movement of the contacts, such as **13**—**14**, **37** and **41**, is also an important feature, which makes my relay respond positively, with less sensitivity to dust or dirt, or to mechanical shocks received when the operating-force is just below the balance-point of the relay, and which also gives the relay a low dropout value, enabling it to readily return to its non-actuated position when the torque-producing conditions return to normal. The disk-construction, with plainly visible airgaps **17′** and **18′** between the disk and the stator-structures, makes for ready inspection to detect the presence of lint or dirt bridging this airgap or clearance-space so as to facilitate keeping the relay in operating order. The compactness of the design, and the utilization of every possible square inch of disk-surface area on both sides of the disk, all make for large torques in a small space or volume, and with a small mass or inertia of the rotor-member, which means a very high speed of operation, ranking my relay foremost in performance, in the family of high-speed alternating-current relays.

As compared to previous induction-type relays, my relay, as shown in Figs. 1, 2 and 3, presents the very great advantage of having the two fluxes which are out of phase with each other on opposite sides of the disk, with separate magnetic-circuit structures provided for each, thus avoiding the leakage-flux and cross-flux troubles which are so prevalent in structures in which a single magnetizable stator-member provides poles carrying both current-responsive and voltage-responsive fluxes. The separation of the current- and voltage-responsive fluxes in two separate magnetic circuits also presents the advantage that any small stray-current torques may be readily balanced out by a slight rotating adjustment or turning of the lower multipolar assembly **18** with respect to the upper multipolar assembly **17**.

As previously intimated, and as will be obvious from the descriptions and illustrations so far given, the broad principles of my invention, or some of them, are susceptible of general applications in other forms of embodiment than those shown in Figs. 1, 2 and 3. Thus, the invention might be applied to an overcurrent relay or an undervoltage relay, an impedance relay, a differential relay, a directional or wattmetric relay, a reactance or modified-reactance relay, or relays producing other effects or combinations of torques, either utilizing the upper multipolar magnetic structure **17** alone, with proper excitation, or (preferably) utilizing both the upper and lower structures, either in cooperation with each other, or to produce separate torques independently of each other. Some of these alternative forms of construction and embodiment of my invention will now be described with reference to the remaining figures of the drawing.

In Figs. 4 and 5, I show my invention applied to a construction in which the torque-producing rotor-member is in the form of a hollow cylinder **10′**, which is supported, from one end, on a shaft-carried disk, spider, or other supporting-member **50** which extends out from the shaft and supports the cylinder **10′** in such manner that the rest of the cylinder, other than the small part which is in contact with the disk or end-closure **50**, is an open-ended extending-portion extending in an axial direction in a spaced concentric relation with respect to the shaft. The cylinder 10′ and the supporting disk 50 together constitute a cup-shaped member, so that the relay is sometimes referred to as a cylinder-type relay, sometimes, less accurately, as a cup-type relay, although the torque is produced essentially only in the cylindrical part of the rotor-member.

In the cylinder-type relay shown in Figs. 4 and 5, the stator-member is also preferably in two parts, comprising an inner magnetizable flux-producing part 51, which extends up into the cylinder 10′, inside thereof, and an outer laminated magnetizable multipolar flux-producing portion 51′ which surrounds the cylinder 10′.

The inner stator-member 51, in common with the other magnetizable members utilized with my present invention, comprises a plurality of salient pole-pieces of more than one polarity. In this case, the pole-pieces of the inner magnetizable structure 51 have pole-face members 52 which are preferably cylindrically curved, so as to present a uniform minimum airgap 52′ with respect to the inner surface of the cylinder 10′, and these pole-face members 52 are preferably rectangularly shaped, so that all four pole-face members 52, together, will substantially cover, with airgap separation, the entire inner surface of the cylinder 10′, except for the necessary spacings between the pole-face members 52, and the necessary end-spaces where the cylinder 10′ extends axially beyond the ends of the pole-face members 52, in both directions, thus providing spaces on the cylindrical surface where the eddy-currents can flow in a manner which will be understood from the description in connection with the disk-type construction.

In Figs. 4 and 5, I utilize a single exciting-coil 53 for the inner multipolar stator-member 51, this coil 53 being preferably the current-energized coil, and being mounted on a magnetizable core-member 54 which is shown in the form of a piece of iron or steel tubing, which performs the function of the previously described yoke-members. Alternate pole-face members 52 are secured to opposite ends of the core-member 54, by means of two spider-members 55 and 56, one at each end of the core-member 54, constituting the several pole-shank portions to which alternate pole-face portions 52 are attached. Thus, in Figs. 4 and 5, there are four pole-face portions 52; and these pole-face portions are connected in diametrical pairs to the respective spider-members 55 and 56 at opposite ends of the core-member 54, so that the pole-face members 52 are alternately north and south poles, at any given instant.

In Figs. 4 and 5, the outer magnetic stator-structure 51′ is provided with four (or other plurality of) salient pole-pieces 57, corresponding to the number of the inner pole-pieces 52. The outer pole-pieces 57 project inwardly from a laminated yoke-structure 58, and which terminate in rectangularly shaped, cylindrical-surfaced pole-face portions 59, which are spaced from the outer surface of the rotor-cylinder 10′ by means of an airgap 60. The shank-portions of the pole-pieces 57 carry coils 61, which are preferably the voltage-energized coils of the relay.

The operation of the cylinder-type form of embodiment of my invention, as shown in Figs. 4 and 5, will be apparent, it is believed, from the foregoing description, particularly in view of the detailed explanation of the operation in connection with Figs. 1, 2 and 3. Two groups of eddy-currents are induced in the rotor-cylinder 10′, one set in response to the current-responsive fluxes of the inner magnetizable stator-structure 51, while the other set of eddy-currents is produced around the pole-face portions 59 of the outer stator-poles 57 in response to the voltage-responsive flux of the stator-member; and these two sets of eddy-currents in the rotor-cylinder 10′ produce a double torque, responsive to the product of the two stator-fluxes, multiplied by a function of the phase-angle between them. The same advantages of compactness, low inertia, and the like, are obtained with my cylinder-type construction, as with my disk-type construction, plus the advantage of requiring only a single current-responsive coil, and the advantage of very great compactness of construction, which results from the cylindrical shape of the torque-producing member and the use of an inner stator-field structure 51 as well as an outer stator-field structure 51′. Furthermore, during short-circuits, when large vibrational forces act on the cylinder, they act radially on the cylinder, and are balanced, so that they produce a minimum amount of vibration of the cylinder.

In Fig. 6, I illustrate how the general principles of my invention may be embodied in a relay of the differential or impedance type, wherein two opposite torques are to be compared, or combined in opposition to each other. In the case of the differential relay, these opposite torques may be produced by two different currents, or by any other two different electrical quantities which are to be differentially compared. In the case of an impedance-relay, these two opposite torques are responsive, respectively, to the line-current and the line-voltage, so that the relay will respond when the ratio of the current to voltage exceeds a predetermined amount, corresponding to a predetermined line-impedance.

In the form of embodiment of my invention which is shown in Fig. 6, the connections are shown for an impedance-relay having a shaft 64 carrying two spaced disks 65 and 66, both mounted on the shaft at right angles thereto and in spaced parallel relation to each other. The shaft 64 is shown as a vertical shaft. The upper disk 65 is surmounted by an upper magnetizable stator-structure 17″, which is spaced from the upper disk 65 by an airgap 17′. Below the lower disk 66, there is provided a second magnetizable stator-structure 18″, which is spaced from the lower disk 66 by an airgap 18′. Between the two disks 65 and 66 is disposed a magnetizable stator member 67 which is spaced from the two disks by air gaps 65′ and 66′, respectively. The central magnetizable stator-member 67 is preferably of sufficient cross-sectional area, for circumferentially rotating fluxes, to avoid saturation in the manner previously described for the pole-face portions 22 in Fig. 3.

In Fig. 6, it is necessary to utilize means for producing a rotatably progressing flux in the successive pole-face portions 22 of both the upper and lower magnetizable stator-members 17″ and 18″, and to this end I show alternate poles as being provided with lag-rings 68. In this construction, it is necessary to utilize two north poles followed by two south poles, at any instant, so that the minimum possible number of poles is four, for each of the two multipolar magnetizable structures 17″ and 18″. The lag-rings 68 produce a lagging of the flux therein, thus producing the well-known rotating-flux effect. The centrally disposed magnetizable stator-member 67, between the two disks 65 and 66, serves simply as a return flux-path for the flux traversing the several disks 65 and 66 from their respective stator-members 17'' and 18'', so that the upper disk 65 develops a torque proportional to the square of the flux in the upper stator-magnet structure 17'', whereas the lower disk 66 develops a torque proportional to the square of the flux in the lower stator magnet-structure 18'', and these two torques can be combined, in opposition to one another, to constitute the operating-torque of the relay.

In order to illustrate that the current-responsive magnet-structure does not need to be above the disk-structure, although such disposition is advantageous, as described in connection with Figs. 1, 2 and 3, I have shown, in Fig. 6, a method of construction in which the lower magnet-structure 18'' is excited in response to the line-current I—I', receiving its energization through an adjustable autotransformer 70, the adjustment of which may be finely adjusted by a vernier-potentiometer or variable-resistance 71 connected across the variable part of the autotransformer 70. The upper field-magnet structure 17'' in Fig. 6 is energized in response to the line-voltage, as indicated by the terminals E and E'. The relay of Fig. 6 thus develops an operating-torque responsive to the square of the line-current, in the lower disk 66, and a restraining-torque responsive to the square of the line-voltage, in the upper disk 65, thus constituting an impedance-relay.

In Fig. 7, I have shown my invention embodied in a novel type of reactance-relay or modified-reactance relay. Structurally, the relay is, or may be, similar to that which is shown in any of Figs. 1 to 5. It has been represented diagrammatically in Fig. 6, in the manner used for Fig. 3. The upper magnet-frame 17 is provided with the current-responsive coils 31, while the lower magnet-frame 18 has not only the previously described voltage-coils 32, but also a set of current-responsive coils 32'. Line-current is supplied from the terminals I and I', through an adjustable autotransformer 75 with which is associated a vernier-adjustment potentiometer 71'. This line-current is supplied to both sets of current-coils 31 and 32'. The voltage-coils 32 are energized from the line-voltage E—E' through a phase-adjusting and magnitude-adjusting impedance, shown as comprising a variable capacitor 76 and a serially connected variable resistance 77.

In the adjustment and operation of the relay shown in Fig. 7, the relative phases and proportionality-ratios of the current-responsive flux produced in the upper magnet 17 and the voltage-responsive flux-component produced in the lower magnet 18 may be adjusted by the autotransformer 75 and the variable impedance 76—77. The voltage-coils 32 act as short-circuited turns on the poles of the lower-magnet frame 18, with respect to the current-responsive flux-component in these same poles, thus producing a lagging phase-angle of this current-responsive flux-component with respect to the unshaded current-responsive flux in the poles of the upper-magnet frame 17, producing a torque equal to KI^2, I being the line-current, and K being a constant. The purely current-responsive flux in the upper magnet-frame 17 cooperates with the voltage-responsive flux-component in the lower-magnet frame 18 to produce a torque equal to $kEI \cos (\alpha \pm \theta)$, where E is the line-voltage, k is a constant, α is a fixed angle of any predetermined value which can be predetermined by adjusting the phase-angle of the impedance 76—77, and θ is the phase-angle between line-current and the line-voltage. There is no torque produced by the product of the fluxes produced by the current and voltage-coils 32' and 32 on the lower poles, since they are not displaced in space with respect to each other. If the current-responsive torque is an operating-torque, the voltage-current-angle-responsive torque will be a restraining torque, at least for certain angles.

The total torque T produced in the relay may be written

$$T = KI^2 - kEI \cos (\alpha - \theta) \tag{1}$$

If the fixed angular displacement α is 90°, the torque becomes

$$\begin{aligned} T_1 &= KI^2 - kEI \sin \theta \\ &= kI^2\left(\frac{K}{k} - \frac{E}{I} \sin \theta\right) \\ &= kI^2\left(\frac{K}{k} - X\right) \end{aligned} \tag{2}$$

where X is the line-reactance. This torque is positive if the line-reactance X is less than K/k, and the torque is negative if X is greater than K/k, the relay being adjusted so that it will respond to a positive torque, and fall back, or fail to respond, in the presence of a negative torque.

If the predetermined fixed angle α is zero, the torque becomes

$$\begin{aligned} T_2 &= KI^2 - kEI \cos \theta \\ &= kI^2\left(\frac{K}{k} - \frac{E}{I} \cos \theta\right) \\ &= kI^2\left(\frac{K}{k} - R\right) \end{aligned} \tag{3}$$

where R is the line-resistance. The relay thus becomes a resistance-responsive relay.

For intermediate values of the fixed angle α, the relay of Fig. 7 becomes a modified-reactance relay, responsive to both the line-reactance X and the line-resistance R, developing a torque,

$$\begin{aligned} T &= KI^2 - kEI \cos (\alpha - \theta) \\ &= KI^2 - kEI (\cos \alpha \cos \theta + \sin \alpha \sin \theta) \\ &= kI^2\left(\frac{K}{k} - \frac{E}{I} (\cos \alpha \cos \theta + \sin \alpha \sin \theta)\right) \\ &= kI^2\left(\frac{K}{k} - R \cos \alpha - X \sin \alpha\right) \end{aligned} \tag{4}$$

This modified-reactance torque-response, as set forth in (4), is obviously a straight line, when plotted on coordinates representing the line-reactance X and the line-resistance R, respectively, the torque-line slanting down from a limiting line-reactance (without resistance) of

$$X_0 = \frac{K}{k} \csc \alpha - R \cot \alpha \tag{5}$$

to a limiting line-resistance (without reactance) of

$$R_0 = \frac{K}{k} \sec \alpha - R \tan \alpha \tag{6}$$

This modified-reactance response, as indicated in Equation 4, is thus a straight-line response, whereas the response of the previously known modified-reactance relay was an arc of a circle, as set forth in the Lewis patent, 1,967,093, granted July 17, 1934, and assigned to the Westinghouse Eelctric and Manufacturing Company.

It is obvious that this new straight-line modified-reactance relay, either in the general case, or in the limiting cases in which the relay responds to pure reactance or to pure resistance, may be carried out by any electroresponsive means which produces the torques set forth in Equations 2, 3, and 4, that is, any apparatus which produces an operating-force responsive to the square of a single-phase current, and a restraining-force responsive to the product of said current, times a single-phase voltage, times the sine (or cosine) of an angle equal to a constant angle plus or minus the phase-angle between the current and the voltage to which the device responds. It is obviously not necessary, so far as the result is concerned, to use the particular means which I have shown, for producing these two opposing torques, although my novel form of relay, as shown, provides an excellent medium for carrying out this novel idea respecting a modified-reactance response.

In Fig. 7, it will be noted that an essential condition concerning the operation of the relay is that the current-responsive flux-component in the lower magnet-frame **18** shall be out of phase with the current-responsive flux-component in the upper magnet-frame **17**; and that the voltage-responsive flux in the lower magnet-frame **18** shall bear a predetermined phase-relationship, such as $(\alpha-\theta)$, with respect to the current-responsive flux in the upper magnet-frame **1**. Any means for bringing about, or controlling, these several phase-relationships will be satisfactory, including, for example, the current-shifting means shown in connection with the overcurrent element **36** of Fig. 3; and I desire Fig. 7 to be understood, in a generic sense, as symbolic of any suitable means for providing the stated phase-relationships between the several fluxes.

While I have described my invention, and explained its principles of operation, in connection with several different specific forms of embodiment, I wish it to be understood that my invention is not altogether limited thereto, as many changes and adaptations will be obvious to those skilled in the art. I desire, therefore, that the appended claims shall be accorded the broadest construction consistent with their language.

I claim as my invention:

1. An alternating-current electro-responsive device comprising a light-weight, rotatably mounted, torque-producing member comprising a light-weight, substantially non-magnetizable, continuous, sheet-like, conducting-portion having a surface which returns circularly on itself, and a stator-member comprising two magnetizable multipolar flux-producing means disposed one on either side of said rotor-member, with airgaps in between, each multipolar flux-producing means comprising a set of salient magnetizable pole-pieces having pole-face portions separated from said sheet-like conducting-portion by one of said airgaps, the front faces of the plurality of pole-face portions of each multipolar flux-producing means being of such shape and area as to cover (through the airgap) substantially the entire available eddy-current-producing and effective torque-producing surface of said sheet-like conducting-portion, with uncovered portions of adequate size but of a size only corresponding to certain necessary rotatably shiftable eddy-current paths in the sheet-like conducting-portion, the poles of one multipolar flux-producing means being displaced in something like a quadrature space-relation with respect to the poles of the other, whereby the flux from or to each pole of each of the multipolar flux-producing means crosses both airgaps and the sheet-like conducting-portion and flows circumferentially in the pole-face portions of two poles of the other multipolar flux-producing means.

2. An alternating-current wattmeter-type electro-responsive device comprising a light-weight, rotatably mounted, substantially non-magnetizable, continuous, sheet-like, conducting-portion having a surface which returns circularly on itself, and a stator-member comprising two magnetizable multipolar flux-producing means disposed one on either side of said sheet-like conducting-portion with airgaps in between, each multipolar flux-producing means comprising a set of salient pole-pieces of alternately opposite polarities succeeding one another and extending all the way around a complete circle, the poles of one multipolar flux-producing means being displaced in something like a quadrature space-relation with respect to the poles of the other, exciting-winding means operatively associated with the respective multipolar flux-producing means for producing magnetic fluxes in the salient pole-pieces, and two single-phase terminal-means, each adapted to be energized for energizing the entire exciting-winding means for the entire sets of pole-pieces of one of said multipolar flux-producing means, whereby a torque is produced having a magnitude and a direction dependent upon the product of the two magnetic fluxes times a function of the phase-angle between them.

3. An alternating-current wattmeter-type electro-responsive device comprising a light-weight, rotatably mounted, substantially non-magnetizable, continuous, sheet-like, conducting-portion having a surface which returns circularly on itself, and a stator-member comprising two magnetizable multipolar flux-producing means disposed one on either side of said sheet-like conducting-portion with airgaps in between, each multipolar flux-producing means comprising a set of salient pole-pieces of alternately opposite polarities succeeding one another and extending all the way around a complete circle, each pole-piece comprising a magnetizable, pole-face member having its front face presented to the airgap of its multipolar flux-producing means, and a magnetizable pole-shank portion extending back from a small portion of the back face of the pole-face member away from the airgap, and each multipolar flux-producing means having a magnetizable yoke-member providing a return-flux path between the rear ends of the shanks of all of the pole-pieces, the front faces of the plurality of pole-face members of each multipolar flux-producing means being of such shape and area as to cover (through the airgap) substantially the entire available eddy-current-producing and effective torque-producing surface of said sheet-like conducting-portion, with uncovered portions of adequate size, but of a size only corresponding to certain necessary rotatably shiftable eddy-current paths in the sheet-like conducting-portion, the poles of one multipolar flux-producing means being displaced in something like a quadrature space-relation with respect to the poles of the other, exciting-winding means operatively associated with the respective multipolar flux-producing means for producing magnetic fluxes in the salient pole-pieces, and two single-phase terminal-means, each adapted to be energized for energizing the entire exciting-

winding means for the entire set of pole-pieces of one of said multipolar flux-producing means, whereby a torque is produced having a magnitude and a direction dependent upon the product of the two magnetic fluxes times a function of the phase-angle between them, the effective cross-sectional areas of the pole-face members of both of said multipolar flux-producing means, for circumferentially moving fluxes therein, being ample to avoid substantial saturation during maximum-flux operating-conditions.

4. The invention as defined in claim 3, characterized by the portion of the magnetic flux-path including the shanks and yoke-member of at least one of said multipolar flux-producing means including, somewhere, a sufficient cross-sectional restriction to produce substantial saturation under the same maximum-flux operating-conditions which produce no substantial saturation for circumferentially moving fluxes in the pole-face members.

5. An alternating-current electro-responsive device comprising a rotatably mounted shaft, a light-weight disk of electrically conducting material mounted at right angles on the shaft, and a stator-member comprising a magnetizable multipolar flux-producing means disposed on one side of said disk, with an airgap in between, said multipolar flux-producing means comprising a plurality of salient pole-pieces of more than one polarity, each salient pole-piece having a magnetizable, flat, substantially sector-shaped, pole-face member having its front face presented to said airgap, the front faces of the plurality of pole-face members of said multipolar flux-producing means being of such area as to cover (through the airgap) substantially the entire available eddy-current-producing and effective torque-producing surface of said disk, with uncovered disk-portions between the radial edges of adjacent sector-shaped pole-face members, between the outer periphery of each sector-shaped pole-face member and the outer periphery of the disk, and between the inner periphery of each sector-shaped pole-face member and the inner periphery of the disk, said uncovered disk-portions providing a rotatably shiftable disk-path for eddy-currents surrounding each of the sector-shaped pole-face members, said eddy-current disk-paths being of cross-sectional areas which are sufficient at each point, but no more than reasonably sufficient, to accommodate the eddy-current flow without excessive resistance-losses at any point, the successive pole-face members extending all the way around a complete circle.

6. The invention as defined in claim 5, characterized by said stator-member comprising two magnetizable multipolar flux-producing means disposed on opposite sides of the disk, with airgaps in between, each magnetizable flux-producing means being substantially of the nature set forth in claim 5, with the pole-face members of the respective multipolar flux-producing means circumferentially staggered with reference to each other, whereby the eddy-currents induced in the disk by the fluxes from the several pole-face members produce a torque having a magnitude and a direction dependent upon the product of the fluxes in the respective multipolar flux-producing means, multiplied by a function of the phase-angle between them.

7. The invention as defined in claim 5, characterized by said stator-member comprising two magnetizable multipolar flux-producing means disposed on opposite sides of the disk, with airgaps in between, each magnetizable flux-producing means being substantially of the nature set forth in claim 5, with the pole-face members of the respective multipolar flux-producing means circumferentially staggered with reference to each other, whereby the eddy-currents induced in the disk by the fluxes from the several pole-face members produce a torque having a magnitude and a direction dependent upon the product of the fluxes in the respective multipolar flux-producing means, multiplied by a function of the phase-angle between them; the shaft being vertical, the upper coils including current-responsive coils, and the lower coils including voltage-response coils.

8. An alternating-current electro-responsive device comprising a rotatably mounted shaft, a light-weight sheet-like, hollow cylinder of substantially non-magnetizable, electrically conducting material, a supporting-member extending out from the shaft for supporting the cylinder on the shaft in such manner that the cylinder has an open-ended extending-portion extending in an axial direction from said supporting-member and in a spaced concentric relation with respect to the shaft, and a stator-member comprising an inner magnetizable multipolar flux-producing means disposed inside of said open-ended extending-portion of the cylinder, with an airgap in between, said inner multipolar flux-producing means comprising a plurality of salient pole-pieces of more than one polarity, each pole-piece comprising a magnetizable, substantially rectangular-shaped, pole-face member having its front face presented to said airgap, a central, axially disposed core-member, magnetizable pole-shank portions extending out from the two ends of the magnetizable core-member in such manner as to carry the flux of said core-member, the several pole-face members being carried by the several pole-shank portions so as to cause different pole-face members, at displaced points all the way around the circumference, to be magnetized from different ends of the core-member, and exciting-winding means on the core-member for exciting all of the poles of said inner multipolar flux-producing means; said stator-member also comprising an outer magnetizable multipolar flux-producing means encircling the open-ended extending-portion of the cylinder, with an airgap in between, the inner and outer airgaps being on opposite sides of said open-ended extending-portion of the cylinder, said outer multipolar flux-producing means comprising a plurality of salient pole-pieces of more than one polarity, each pole-piece comprising a magnetizable, substantially rectangular-shaped, pole-face member having its front face presented to said airgap, and a magnetizable pole-shank portion extending in a substantially radial direction back from the pole-face member away from the airgap, and a magnetizable yoke-member providing a return-flux path between the rear ends of the shanks of the pole-pieces, the front faces of the plurality of pole-face members of said outer multipolar flux-producing means extending all the way around the circumference in circumferentially staggered relation with respect to the pole-face members of the inner multipolar flux-producing means, whereby the eddy-currents induced in said open-ended extending portion of the cylinder by the fluxes from the several pole-face members produce a torque having a magnitude and a direction dependent upon the product of

the fluxes in the respective multipolar flux-producing means, multiplied by a function of the phase-angle between them, and exciting-winding coils on the respective pole-shanks of the outer multipolar flux-producing means.

9. An alternating-current electro-responsive device comprising a light-weight, rotatably mounted, torque-producing member comprising a light-weight, continuous, sheet-like, conducting-portion having a surface which returns circularly on itself, and a stator-member comprising a magnetizable multipolar flux-producing means disposed on one side of said sheet-like conducting-portion, with an airgap in between, said multipolar flux-producing means comprising a set of salient pole-pieces of more than one polarity, each pole-piece comprising a magnetizable, pole-face member having its front face presented to said airgap and a magnetizable pole-shank portion extending back from a small portion of the back face of the pole face member away from the airgap, and a magnetizable yoke-member providing a return-flux path between the rear ends of the shanks of all of the pole-pieces, the front faces of the plurality of pole-face members of said multipolar flux-producing means being of such shape and area as to cover (through the airgap) substantially the entire available eddy-current-producing and effective torque-producing surface of said sheet-like conducting-portion, with uncovered portions of the sheet-like conducting-portion of adequate size but of a size corresponding to certain necessary rotatable shiftable eddy-current paths in said sheet-like conducting-portion, the successive pole-face members extending all the way around a complete circle, means for producing magnetic fluxes in the respective salient pole-pieces, a common electric-circuit terminal-means adapted to be energized for energizing the means for producing the magnetic fluxes with a variable single-phase electrical quantity, and dephasing-means associated with some of said pole-pieces for causing the flux therein to differ, in phase, from the flux in some other pole-pieces, whereby a rotating flux-field is produced, said stator-member further comprising a second magnetizable-flux-carrying member disposed on the opposite side of said sheet-like conducting-portion, with an airgap in between, said second magnetizable flux-carrying member providing a flux-path for circumferentially moving fluxes between pole-pieces of different polarities.

10. An alternating-current electro-responsive device having a double rotatably mounted torque-producing member comprising two light-weight, continuous, sheet-like conducting-portions held in fixedly and uniformly spaced relation with respect to each other; and a stator-member comprising two magnetizable multipolar flux-producing means disposed on opposite sides of the double rotatably mounted torque-producing member, each of said multipolar flux-producing means being associated, with airgap separation, with a different one of said two conducting-portions of the rotatably mounted member; each of said multipolar flux-producing means comprising a set of salient pole-pieces of more than one polarity, each pole-piece comprising a magnetizable, pole-face member having its front face presented to the airgap and a magnetizable pole-shank portion extending back from a small portion of the back face of the pole face member away from the airgap, and a magnetizable yoke-member providing a return-flux path between the rear ends of the shanks of all of the pole-pieces, the front faces of the plurality of pole-face members of said multipolar flux-producing means being of such shape and area as to cover (through the airgap) substantially the entire available eddy-current-producing and effective torque-producing surface of the associated sheet-like conducting-portion, with uncovered portions of the sheet-like conducting-portion of adequate size but of a size corresponding to certain necessary rotatably shiftable eddy-current paths in said sheet-like conducting-portion, the successive pole-face members extending all the way around a complete circle; said stator-member further comprising an intermediate magnetizable flux-carrying means disposed between the two conducting-portions, with airgaps in between; exciting-winding means operatively associated with the respective multipolar flux-producing means for producing rotating magnetic fluxes in the respective sets of pole-pieces, and terminal-means adapted to be electrically energized for variably energizing the exciting-winding means.

11. An alternating-current wattmeter-type electro-responsive device comprising a light-weight, rotatably mounted, substantially non-magnetizable, continuous, sheet-like, conducting-portion having a surface which returns circularly on itself, and a stator-member comprising two magnetizable multipolar flux-producing means disposed one on either side of said sheet-like conducting-portion with airgaps in between, each multipolar flux-producing means comprising a set of salient pole-pieces of alternately opposite polarities succeeding one another and extending all the way around a complete circle, the poles of one multipolar flux-producing means being displaced in something like a quadrature space-relation with respect to the poles of the other, exciting-winding means operatively associated with one of the multipolar flux-producing means for producing single-phase current-responsive magnetic fluxes in the several salient pole-pieces of that multipolar flux-producing means, and exciting-winding means operatively associated with the other multipolar flux-producing means for producing single-phase current-and-voltage-responsive magnetic fluxes in the several salient pole-pieces of that multipolar flux-producing means; the current-responsive component of the flux in the last-mentioned multipolar flux-producing means being out of phase with the flux in the first-mentioned multipolar flux-producing means; and the voltage-responsive component of the flux in the second-mentioned multipolar flux-producing means being displaced from the flux in the first-mentioned multipolar flux-producing means by a phase-angle equal to a constant angle plus or minus the phase-angle between the current and the voltage to which the device responds.

12. The invention as defined in claim 11, characterized by said constant angle being such that the torque produced by the current-responsive flux in the first flux-producing means and the voltage-responsive flux-component in the second flux-producing means is substantially proportional to the current times the voltage times the sine of the phase-angle between the current and the voltage.

13. An alternating-current wattmeter-type electro-responsive device comprising a light-weight, rotatably mounted, substantially non-magnetizable, continuous, sheet-like, conducting-portion having a surface which returns circularly on itself, and a stator-member comprising two

magnetizable multipolar flux-producing means disposed one on either side of said sheet-like conducting-portion with airgaps in between, each multipolar flux-producing means comprising a set of salient pole-pieces of alternately opposite polarities succeeding one another and extending all the way around a complete circle, the poles of one multipolar flux-producing means being displaced in something like a quadrature space-relation with respect to the poles of the other, exciting-winding means operatively associated with one of the multipolar flux-producing means for producing single-phase current-responsive magnetic fluxes in the several salient pole-pieces of that multipolar flux-producing means, and exciting-winding means operatively associated with the other multipolar flux-producing means for producing single-phase current-and-voltage-responsive magnetic fluxes in the several salient pole-pieces of that multipolar flux-producing means.

14. A single-phase wattmeter-type electro-responsive device having a stator-member comprising a magnetizable structure including a plurality of salient pole-pieces extending around a complete circle at circumferentially spaced points, exciting-winding means for causing alternate pole-pieces to be traversed by different ones of two single-phase magnetic fluxes susceptible of having a difference in time-phase therebetween, and a rotor-member having conducting-means disposed in the airgap in front of the several salient pole-pieces in such manner as to have a pole-encircling secondary-current circuit surrounding each pole-piece, with current induced therein by the magnetic flux of said pole-piece, each secondary-current circuit having a substantial proportion of two sides of its current-path lying in good torque-producing position in the portion of the airgap in front of the two adjacent pole-pieces lying on opposite sides of the current-inducing pole-piece, whereby a rotor-torque is produced, proportional to the product of the two single-phase fluxes multiplied by a function of the time-phase between them.

15. The invention as defined in claim 14, characterized by the conducting-means of said rotor-member comprising a continuous, sheet-like conducting-portion having a surface which returns circularly on itself.

16. The invention as defined in claim 14, characterized by the conducting-means of said rotor-member comprising a disk of electrically conducting material mounted at right angles on the rotor-shaft.

17. The invention as defined in claim 14, characterized by the conducting-means of said rotor-member comprising a sheet-like hollow cylinder of electrically conducting material mounted for rotation about its axis.

18. A single-phase wattmeter-type electro-responsive device adapted for use on an alternating-current system and having a stator-member including two flux-producing winding-means for producing two single-phase magnetic fluxes susceptible of having a difference in time-phase therebetween, and a rotor-member so disposed as to produce a torque which is proportional to the product of the two single-phase fluxes multiplied by a function of the time-phase between them, in combination with electric energizing-means for energizing the two flux-producing winding-means in response to electrical quantities derived from said alternating-current system in such manner that at least one of said fluxes is responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage.

19. A single-phase wattmeter-type electro-responsive device adapted for use on an alternating-current system and having a stator-member including two flux-producing winding-means for producing two single-phase magnetic fluxes susceptible of having a difference in time-phase therebetween, and a rotor-member so disposed as to produce a torque which is proportional to the product of the two single-phase fluxes multiplied by a function of the time-phase between them, in combination with electric energizing-means for energizing the two flux-producing winding-means in response to electrical quantities derived from said alternating-current system in such manner that one of said fluxes is responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage, and in such manner that the other of said fluxes is responsive to a line-current.

20. A single-phase wattmeter-type electro-responsive device adapted for use on an alternating-current system and having a stator-member including two flux-producing winding-means for producing two single-phase magnetic fluxes susceptible of having a difference in time-phase therebetween, and a rotor-member so disposed as to produce a torque which is proportional to the product of the two single-phase fluxes multiplied by a function of the time-phase between them, in combination with electric energizing-means for energizing the two flux-producing winding-means in response to electrical quantities derived from said alternating-current system in such manner that one of said fluxes is responsive to the vectorial sum of an alternating-current function of a line-current and an alternating-current function of a line-voltage, and in such manner that the other of said fluxes is responsive to the same line-current which combines with the line-voltage to control the first-mentioned flux.

21. The invention as defined in claim 1, characterized by the spacings between the pole-face portions of each multipolar flux-producing means being of the order of ¼ inch, and the spacing between the outer edge of the entire assembly of pole-face portions and the outer edge of the sheet-like, rotatably mounted conducting-portion being also of the order of ¼ inch.

22. The invention as defined in claim 2, characterized by the spacings between the pole-face portions of each multipolar flux-producing means being of the order of ¼ inch, and the spacing between the outer edge of the entire assembly of pole-face portions and the outer edge of the sheet-like, rotatably mounted conducting-portion being also of the order of ¼ inch.

23. The invention as defined in claim 3, characterized by the spacings between the pole-face portions of each multipolar flux-producing means being of the order of ¼ inch, and the spacing between the outer edge of the entire assembly of pole-face portions and the outer edge of the sheet-like, rotatably mounted conducting-portion being also of the order of ¼ inch.

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