July 10, 1945. A. C. MEHRING 2,380,187

UNIVERSAL HIGH-SPEED DIRECTIONAL RELAY

Filed Jan. 12, 1944

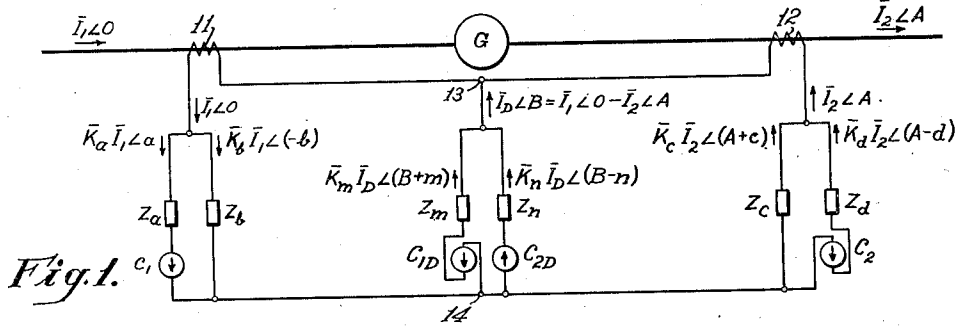


Fig. 1.

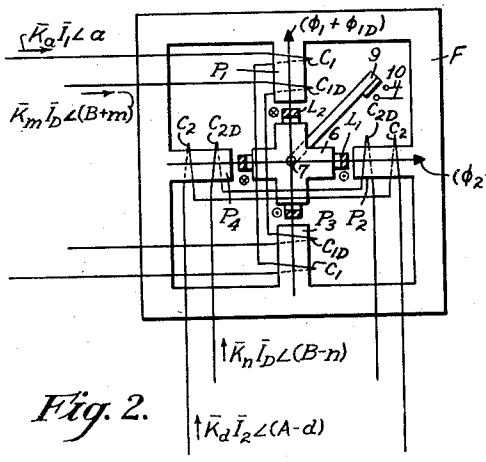


Fig. 2.

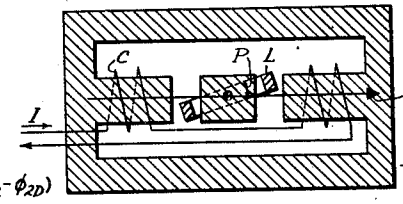


Fig. 3.

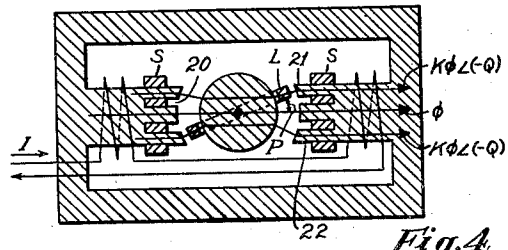


Fig. 4.

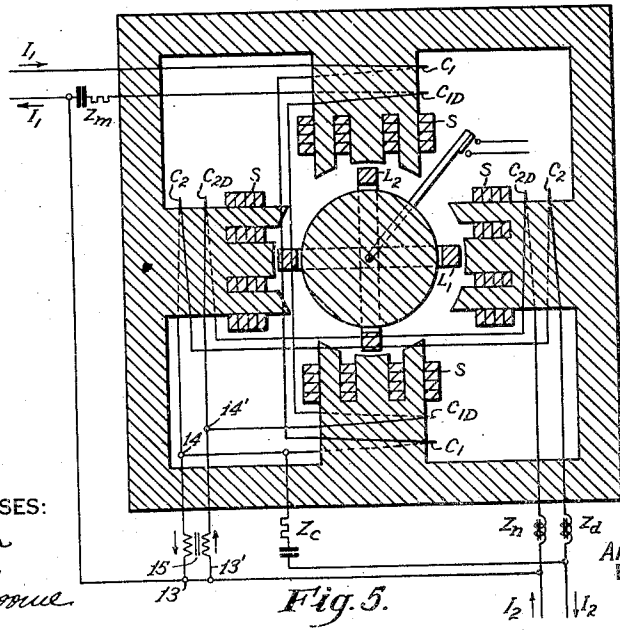


Fig. 5.

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UNIVERSAL HIGH-SPEED DIRECTIONAL RELAY

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16 Claims. (Cl. 175—294)

My invention relates to directional relay-elements and similar devices, particularly single-phase devices having two alternating fluxes, for producing a torque responsive to the product of the two fluxes, times a function of the phase-angle between said fluxes. My invention has particular relation to a non-vibratory single-phase, two-flux relay having a conducting secondary or rotor member in which each flux induces secondary currents which flow in paths having some torque-producing relation with the other flux, whereby the double-frequency components of the useful torque may be eliminated. In the preferred forms of embodiment of my invention, this secondary member is a double-loop design.

In an application of William K. Sonnemann, Shirley L. Goldsborough and myself, Serial No. 516,238, filed December 30, 1943, the general principles of a substantially non-vibratory, product-responsive, single-phase, torque-producing relay-element are described and claimed, in the form of a double-loop rotor-design, or equivalent secondary-member design, wherein the double-frequency components of the single-phase torque are eliminated.

In an application of Shirley L. Goldsborough Serial No. 503,367, filed September 22, 1943, a universal, high-speed relay-element is described and claimed, in the form of a wattmetric or directional element which responds to $(E+I)(E-I)$.

An object of my present invention is to enlarge the utility and applicability of the above-described inventions by producing a two-flux, single-phase, directional relay-element, in combination with phase-shifting means, so that the relay may be directionally responsive to any two exciting-currents, whether these currents are derived from line-currents, or line-voltages, or any other two single-phase electrical quantities of the same frequency, but of variable phase relations and/or magnitudes.

More specifically, it is an object of my invention to utilize relay-connections and phase-shifting devices so that one of the relay-fluxes is responsive, in any degree of magnitude, to one of the two alternating control-currents, at any phase-angle with respect to said control-current, vectorially combined with a response, in any degree of magnitude, to the difference between the two alternating control-currents, dephased by any desired phase-angle; while the other relay-flux is differentially vectorially responsive to, in general, a different magnitude and phase-angle response to the second alternating control-current, and to, in general, a different magnitude and phase-angle response to the difference between the two alternating control-currents.

A more specific object of my invention relates to the provision of a new type of high-speed differential relay, in which the two alternating control-currents are single-phase input and output currents derived from a device, such as an alternating-current generator, which is to be differentially protected, the relay constants, as to magnitudes and phase-angles, being suitably chosen to bring about this result, in a manner which will be more specifically described.

A still further object of my invention is to provide a shaded-pole means, or equivalent construction, for increasing the sensitivity of an induction-loop relay-element, by eliminating an unwanted "centering" bias-torque which would prevent the relay from responding to a very weak useful operating-torque.

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

Figure 1 is a circuit-diagram showing the relay-connections, including phase-shifting and magnitude-control means for controlling the energization of the four relay-coils, as will be subsequently described,

Fig. 2 is a diagrammatic view of a simple form of the improved relay, utilizing the four coils which may be energized as shown in Fig. 1,

Fig. 3 is a diagrammatic view of a simple, induction-loop relay, which will be referred to in discussing the unwanted "centering" biasing-torque which results from a displacement of the plane of the induction-loop from alignment with the direction of flow of the magnetic flux,

Fig. 4 is a view of the same simple relay-element as Fig. 3, modified by the addition of pole-shading lag-loops on the pole-tips, for eliminating the unwanted "centering" biasing-torque, and

Fig. 5 is a diagrammatic view of an exemplary form of embodiment of my improved relay, including both the universal relay-responsive characteristics of Figs. 1 and 2, and the centering-torque elimination of Fig. 4.

In Fig. 2, I have shown a four-pole relay-design in which the stator-member consists of a laminated magnetizable frame F having four salient pole-pieces P_1, P_2, P_3, and P_4, and preferably also including a centrally disposed stationary laminated magnetizable core-member 6, which is separated from the pole faces of the various field-

poles, by airgaps. Disposed within the airgaps just mentioned, is a rotor-member which is preferably in the form of two loops L_1 and L_2. The plane of the loop L_1 is coincident with the center-lines of the diametrically opposite poles P_2 and P_4, with the loop-sides lying in the airgaps under these two poles, while the other loop L_2 is similarly disposed with respect to the other two diametrically opposite poles P_1 and P_3. The two loops are rigidly connected together and mounted on a pivot **7** which may carry a relay contact-arm **9** for controlling any desired controlled-circuit **10**.

The relay of Fig. 2 is excited so as to have two diametrically flowing fluxes, the flux $(\phi_1+\phi_{1D})$ flowing through the diametrically opposite poles P_3 and P_1, while the flux $(\phi_2-\phi_{2D})$ flows in the other two diametrically opposite poles P_4 and P_2. Four coils, C_1, C_{1D}, C_2, and C_{2D}, are provided for producing the two relay-fluxes $(\phi_1-\phi_{1D})$ and $(\phi_2-\phi_{2D})$. The coils C_1 and C_{1D} are each split into two parts, with one part on each of the two diametrically opposite poles P_1 and P_3. In like manner, the coils C_2 and C_{2D} are each split into two parts, with one part on each of the poles B_2 and B_4. Each flux flows diametrically across the relay-element, leaving one pole, traversing the two diametrically opposite airgaps, and entering the diametrically opposite pole.

In accordance with one feature of my invention, a special relay-circuit connection, including phase-shifting means, is utilized for energizing the four relay-coils C_1, C_{1D}, C_2 and C_{2D}, in such manner that the coil C_1 is predeterminedly responsive to an alternating control-current I_1, with any phase-angle shift a therebetween, while the relay-coil C_2 is responsive to a second alternating control-current I_2, generally with a different magnitude of response, and a different phase-shift angle such as $(-d)$. The other two relay-coils C_{1D} and C_{2D} are responsive to the vectorial difference of the two alternating control-currents I_1 and I_2, or $I_D=I_1-I_2$. The magnitudes and the phase-angle shifts, of the responses of the relay-coils C_{1D} and C_{2D}, with respect to the differential current I_D, are in general different, so that the phase-angle of the exciting-current in the coil C_{1D} is shifted by an angle such as m, while the exciting-current in the coil C_{2D} is shifted by an angle such as $(-n)$.

In the particular system of relay-connections shown in Fig. 1, the relay is utilized as a differential relay for differentially protecting the windings of a generator G, and the two relay-controlling currents I_1 and I_2 are derived from the terminal-currents which enter and leave the generator G, respectively. In Fig. 1, the absolute or scalar values of the various vectors are utilized, as indicated by a bar placed above the symbol in question, and the phase-angle is indicated by the phase-angle sign $\angle$ followed by the designation of the phase-angle by which the current in question leads a predetermined datum, which is taken as the phase of the line-current I_1.

The system of relay-circuit connections shown in Fig. 1 utilizes two line-current transformers **11** and **12** for deriving the relaying currents $\bar{I}_1\angle O$ and $\bar{I}_2\angle A$, respectively. The two current-transformers **11** and **12** are connected to a common connection **13** which supplies the difference-current

$$\bar{I}_D\angle B=\bar{I}_1\angle O-\bar{I}_2\angle A$$

In accordance with my invention, as shown symbolically in Fig. 1, any suitable phase-shifting means or network is associated with any one, or two, or all three, of the currents I_1, I_2 and I_D, respectively. Any suitable phase-shifting means may be utilized, but for simplicity of illustration, I have shown, in each case, merely two branch-circuits including properly chosen impedances, although other known phase-shifting means may be economically more suitable. Thus, the current I_1 is fed through two circuits, containing the phase-shifting impedances Z_a and Z_b, respectively, to a common star-point connecting **14**, the current $(-I_2)$ is similarly fed to the common connection **14** through two circuits containing the phase-shifting impedances Z_c and Z_d, and the current $(-I_D)$ is similarly fed to the common connection **14** through two circuits containing the phase-shifting impedances Z_m and Z_n.

The relay-coils C_1, C_2, C_{1D} and C_{2D} are connected in series, respectively, in the branch-circuits which contain the phase-shifting impedances Z_a, Z_d, Z_m and Z_n, respectively, being traversed by currents which, in general, bear different proportionality or magnitude-ratios, $\bar{K}_a$, $\bar{K}_d$, $\bar{K}_m$ and $\bar{K}_n$, with respect to the various control-currents I_1, I_2 and I_D, and having also, in general, different phase-angular relationships, as indicated. The various relay-coils C_1, C_2, C_{1D} and C_{2D} may all have the same number of turns, or if the numbers of turns are different, that fact can be taken into consideration in the designation of the various proportionality-constants K.

The relay of Figs. 1 and 2 is a universal relay, so that the same type and construction of relay may be utilized for any one of a large number of different functions, according to the choice of constants, which controls the manner of response which is utilized to produce the two relay-fluxes.

In the particular application of my invention which is illustrated in Figs. 1 and 2, the relay is utilized as an improved form of high-speed differential relay-element, which is advantageous in three ways. During internal-fault conditions, the restraining component of torque does not become zero, as has been heretofore the case, in previously known differential relays, but it actually reverses, and becomes an operating torque, tending to cause the relay to operate in response to the internal fault within the protected machine or apparatus G. At the balance-point of my new relay, the opposed operating and restraining forces do not operate upon the bearings, causing loose-play vibration and friction and wear, as in ordinary differential relays, but the two opposing forces are magnetically combined in the electrical quantities, resulting in one torque acting upon the moving element. The instantaneous torque remains constant with respect to time, thereby reducing vibrating torques to a minimum, and giving good contact-characteristics, this result being obtained by reason of the cancellation of the double-frequency component of the torque which results from single-phase energization.

My relay, as shown in Figs. 1 and 2, utilizes two fluxes $(\phi_1+\phi_{1D})$ and $(\phi_2-\phi_{2D})$ as follows:

$$(\phi_1+\phi_{1D})=\bar{K}_1\bar{I}_1\angle a+\bar{K}_{1D}\bar{I}_D\angle(B+m)\text{----}(1)$$

$$(\phi_2-\phi_{2D})=\bar{K}_2\bar{I}_2\angle(A-d)-\bar{K}_{2D}\bar{I}_D\angle(B-n)\text{--}(2)$$

Assuming identical relay-loops L_1 and L_2, (Fig. 2), each introducing a lag-angle $(-q)$ in the loop-currents which are induced by the fluxes $(\phi_1+\phi_{1D})$ and $(\phi_2-\phi_{2D})$, respectively, where q is

somewhat greater than 90°, then the relay-torque (clockwise) will be

$$T=-[\phi_1\angle(-q)+\phi_{1D}\angle(-q)].(\phi_2-\phi_{2D})+[\phi_2\angle(-q)-\phi_{2D}\angle(-q)].(\phi_1+\phi_{1D})$$
$$=-[\bar{K}_1\bar{I}_1\angle(a-q)+\bar{K}_{1D}\bar{I}_D\angle(B+m-q)].[\bar{K}_2\bar{I}_2\angle(A-d)-\bar{K}_{2D}\bar{I}_D\angle(B-n)]+$$
$$+[\bar{K}_2\bar{I}_2\angle(A-d-q)-\bar{K}_{2D}\bar{I}_D\angle(B-n-q)].[\bar{K}_1\bar{I}_1\angle a+\bar{K}_{1D}\bar{I}_D\angle(B+m)]\text{------(3)}$$

The instantaneous torque will be:

$$t=-2[\bar{K}_1\bar{I}_1\sin(wt+a-q)+\bar{K}_{1D}\bar{I}_D\sin(wt+B+m-q)].$$
$$.[\bar{K}_2\bar{I}_2\sin(wt+A-d)-\bar{K}_{2D}\bar{I}_D\sin(wt+B-n)]+$$
$$+2[\bar{K}_2\bar{I}_2\sin(wt+A-d-q)-\bar{K}_{2D}\bar{I}_D\sin(wt+B-n-q)].$$
$$.[\bar{K}_1\bar{I}_1\sin(wt+a)+\bar{K}_{1D}\bar{I}_D\sin(wt+B+m)]\text{----------(4)}$$

Performing the multiplications,

$$t=-2\bar{K}_1\bar{K}_2\bar{I}_1\bar{I}_2[\sin(wt+a-q)\sin(wt+A-d)]+$$
$$+2\bar{K}_1\bar{K}_2\bar{I}_1\bar{I}_2[\sin(wt+A-d-q)\sin(wt+a)]+$$
$$+2\bar{K}_1\bar{K}_{2D}\bar{I}_1\bar{I}_D[\sin(wt+a-q)\sin(wt+B-n)]+$$
$$-2\bar{K}_1\bar{K}_{2D}\bar{I}_1\bar{I}_D[\sin(wt+B-n-q)\sin(wt+a)]+$$
$$-2\bar{K}_{1D}\bar{K}_2\bar{I}_D\bar{I}_2[\sin(wt+B+m-q)\sin(wt+A-d)]+$$
$$+2\bar{K}_{1D}\bar{K}_2\bar{I}_D\bar{I}_2[\sin(wt+A-d-q)\sin(wt+B+m)]+$$
$$+2\bar{K}_{1D}\bar{K}_{2D}\bar{I}_{2D}[\sin(wt+B+m-q)\sin(wt+B-n)]+$$
$$-2\bar{K}_{1D}\bar{K}_{2D}\bar{I}^2{}_D[\sin(wt+B-n-q)\sin(wt+B+m)]\text{----------(5)}$$

Applying the formula for the product of the sines of two angles:

$$t=\bar{K}_1\bar{K}_2\bar{I}_1\bar{I}_2[-\cos(-A+a+d-q)+\cos(2wt+A+a-d-q)]+$$
$$+\bar{K}_1\bar{K}_2\bar{I}_1\bar{I}_2[\cos(A-a-d-q)-\cos(2wt+A+a-d-q)]+$$
$$+\bar{K}_1\bar{K}_{2D}\bar{I}_1\bar{I}_D[\cos(-B+a+n-q)-\cos(2wt+B+a-n-q)]+$$
$$+\bar{K}_1\bar{K}_{2D}\bar{I}_1\bar{I}_D[-\cos(B-a-n-q)+\cos(2wt+B+a-n-q)]+$$
$$+\bar{K}_{1D}\bar{K}_2\bar{I}_D\bar{I}_2[-\cos(-A+B+d+m-q)+\cos(2wt+A+B-d+m-q)]+$$
$$+\bar{K}_{1D}\bar{K}_2\bar{I}_D\bar{I}_2[\cos(A-B-d-m-q)-\cos(2wt+A+B-d+m-q)]+$$
$$+\bar{K}_{1D}\bar{K}_{2D}\bar{I}^2{}_D[\cos(M+n-q)-\cos(2wt+2B+m-n-q)]+$$
$$+\bar{K}_{1D}\bar{K}_{2D}\bar{I}^2{}_D[-\cos(-m-n-q)+\cos(2wt+2B+m-n-q)]\text{----------(6)}$$

The double-frequency terms containing $2wt$ cancel out, leaving a non-pulsatory instantaneous torque t, equal to a steady torque T which may be written:

$$T=2\sin q[\bar{K}_1\bar{K}_2\bar{I}_1\bar{I}_2\sin(A-a-d)+\bar{K}_1\bar{K}_{2D}\bar{I}_1\bar{I}_D\sin(-B+a+n)+$$
$$+\bar{K}_{1D}\bar{K}_2\bar{I}_D\bar{I}_2\sin(A-B-d-m)+\bar{K}_{1D}\bar{K}_{2D}\bar{I}^2{}_D\sin(m+n)]\text{----------(7)}$$

Several variations of the constants may be chosen, to provide desirable relay-characteristics which are readily calculable. For example, I may very advantageously make:

$$\left.\begin{array}{l}a+d=90°\\a+n=45°\\m+d=135°\\m+n=90°\\\bar{K}_1=\bar{K}_2\\\bar{K}_{1D}=\bar{K}_{2D}=\bar{K}_D\end{array}\right\}\text{----------(8)}$$

Substituting these special values of the constants in Equation 7, the relay-torque, distinguished by the subscript 8, is found to be,

$$T_8=2\sin q[-K_2^2\bar{I}_1\bar{I}_2\cos A+\bar{K}_2\bar{K}_D\bar{I}_1\bar{I}_D\cos(B+45°)+$$
$$-\bar{K}_2\bar{K}_D\bar{I}_D\bar{I}_2\cos(B-A+45°)+\bar{K}_D{}^2\bar{I}_D{}^2]\text{--(9)}$$

For the case of a through-fault, indicated by the subscript t, the two line-currents $\bar{I}_{1t}$ and $\bar{I}_{2t}$ will be substantially equal, in Fig. 1; the phase-angles A and B will be substantially zero; the differential current $\bar{I}_{Dt}=\bar{I}_{1t}-\bar{I}_{2t}$ will be substantially zero; and the relay-torque will be a negative or restraining torque, which holds the moving element of the relay back against its backstop, as shown by the equation,

$$T_t=2\sin q[-\bar{K}_2^2\bar{I}_{1t}\bar{I}_{2t}+$$
$$.7\bar{K}_2\bar{K}_D(\bar{I}_{1t}-\bar{I}_{2t})\bar{I}_{Dt}+\bar{K}_D{}^2\bar{I}_{Dt}{}^2]\text{----------(10)}$$

or approximately

$$T_t=2\sin q[-\bar{K}_2^2\bar{I}_{1t}\bar{I}_{2t}+0-0+0]\text{------(11)}$$

since $(\bar{I}_{1t}-\bar{I}_{2t})$ and $\bar{I}_{Dt}$ are both approximately equal to zero (if the line-current transformers 11 and 12 are accurate under fault-conditions).

For the case of an internal fault, indicated by the subscript i, the phase-angle A will usually be close to 180°, in Fig. 1; the phase-angle B will usually be somewhere in the neighborhood of 0; and the relay-torque will be a positive or operating torque, which may be expressed, approximately, as

$$T_i=2\sin q[+\bar{K}_2^2\bar{I}_{1i}\bar{I}_{2i}+.7\bar{K}_2\bar{K}_D\bar{I}_{Di}\bar{I}_{1i}+$$
$$.7\bar{K}_2\bar{K}_D\bar{I}_{Di}\bar{I}_{2i}+\bar{K}_D{}^2\bar{I}_{Di}{}^2]\text{----------(12)}$$

Since the differential current will approximate $\bar{I}_{Di}=\bar{I}_{1i}+\bar{I}_{2i}$, the torque may be expressed, approximately, as

$$T_i=2\sin q[+\bar{K}_2^2\bar{I}_{1i}\bar{I}_{2i}+\bar{K}_D\bar{I}_{Di}{}^2(\bar{K}_D+.7\bar{K}_2)]\text{----(13)}$$

It will be noted that the first term of the torque-Equation 9 represents a directional torque-component, $-\bar{K}_2^2\bar{I}_1\bar{I}_2\cos A$, which is proportional to the product of the two line-currents I_1 and I_2, times the cosine of the angle A between them. This term reverses for an external fault, in comparison with an internal fault, so that it aids the operating-torque, or the torque which is responsive to the differential-current I_D, during internal-fault conditions, when a relay-operation is desired, while it reverses, and restrains the relay against an unwanted response during external-fault or through-current conditions. This is a valuable characteristic of my relay.

It will be noted that the conditions represented by Equations 8 can be satisfied in a number of different ways. For example, as shown in Fig. 5, Z_a of Fig. 1 may be short-circuited, or zero, and Z_b open-circuited, or infinity, in which case the phase-shift angle a would be zero. Then the phase-shift angle d would have to approximate 90°, in which case Z_d would be a high-impedance inductance, and Z_c would be a low-impedance

resistance, or a small resistance with a serially connected capacitance; while the phase-shift angles m and n would both be 45°, which could be accomplished by making Z_m and Z_n have the same absolute impedance, Z_n being an inductance, and Z_m being a resistance, or a resistance with a serially connected capacitance.

If desired, as shown in Fig. 5, an auxiliary current-transformer **15** may be introduced in the difference-current branch, between the conductors **13** and **14**, and its secondary circuit **13'—14'** may be utilized to energize the circuits of the coils C_{1D} and C_{2D}. Such a transformer makes it easy to change or adjust the relative magnitudes of the constants K_2 and K_D in Equations 10 to 13, or it can be given a saturating characteristic which will cause K_D to become smaller as the difference-current increases.

According to one aspect of my invention, the two loops L_1 and L_2 which constitute the rotor of my relay in Fig. 2, may be regarded as representative of any sort of conducting secondary member in which one flux, $(\phi_1+\phi_{1D})$, induces secondary currents which flow in a path or paths having some torque-producing relation with the other flux, $(\phi_2-\phi_{2D})$, and vice versa.

When the rotor-member of the relay is in the form of two induction-loops, L_1 and L_2, as it is, in the preferred forms of embodiment of my invention, the induced secondary currents are caused to flow in paths which fall in the strongest part of the torque-producing flux, so that a maximum relay-torque is produced, with a minimum rotor-mass. Such an induction-loop relay is thus an ideal high-speed element, being inherently high-speed in its action.

However, the sensitivity of the induction-loop relay, in the form shown in Fig. 2, is not as great as certain other known types of relays, such as the induction-disc type or the cup-type. This limitation is chiefly due to a "centering" bias-torque which is not desired, and which acts in opposition to the true operating-torque to which the relay-element should respond. Thus, when the true operating-torque is small, the unwanted bias-torque may become overpoweringly large, preventing the relay from responding sensitively to small operating-torques.

Fig. 3 may be referred to for an understanding of the manner in which this centering bias-torque is produced. It happens when one of the relay-fluxes is quite large, while the other relay-flux is small, so that the useful operating-torque is small. Fig. 3 illustrates a relay-element with only one airgap-flux, ϕ, operating on a loop L, which is displaced from its center position, in line with the flux, by an angle P, so that some of the flux ϕ threads through the loop. The loop-current may be expressed, as before, as equal or proportional to the inducing flux ϕ, displaced by a lag-angle $(-q)$, which will usually have a value somewhere between 100° and 120°. This loop-current will react with the inducing-flux ϕ to produce a centering-torque T_c which tends to force the loop into the one position where none of the flux links the loop. This "centering" biasing-torque may be written,

$$T_c=[\phi\angle(-q)].\phi \quad \text{(14)}$$

$$=\phi^2[\cos(-q)-\cos(2wt-q)] \quad \text{(15)}$$

I have devised means, however, whereby this unwanted centering-torque may be eliminated. I do this, as shown in Figs. 4 and 5, by providing lag-loops or shading-loops S on both the leading and trailing tips of each pole.

Referring to Fig. 4, the poles are slotted, as shown at **20**, to provide shaded pole-tips **21** and **22** on each side of the main central portion of each pole. These shaded pole-tips **21** and **22** are each encircled by one or more pole-shading lag-rings S, which cause a lagging flux, $K\phi\angle(-Q)$, to traverse the pole-tips, while an unshaded flux, ϕ, traverses the main central portions of the poles.

Of the total pole-piece flux, a certain portion, $[K_6\phi+K_7\phi\angle(-Q)]$, interlinks the loop when the latter is inclined at an angle P, inducing a loop-current which lags this flux by $(-q)$. Since the loop is inclined at an angle P, its loop-sides approach the shaded pole-tips **21** and **22**, so that the effective torque-producing flux is more strongly affected by the shading-rings S than the inducing-flux $[K_6\phi+K_7\phi\angle(-Q)]$. This torque-producing flux may be written $[K_8\phi+K_9\phi\angle(-Q)]$, where K_9 and K_6 are, in general, larger than K_7 and K_8, respectively.

The resultant bias-torque may be written

$$T_b=[K_6\phi\angle(-q)+K_7\phi\angle(-Q-q)].[K_8\phi+K_9\phi\angle(-Q)] \quad \text{(16)}$$

$$=\phi^2K_6K_8\cos(-q)+\phi^2K_7K_8\cos(-Q-q)+\phi^2K_7K_9\cos(-q)+\phi^2K_6K_9\cos(Q-q)+$$

$$+\text{some double-frequency terms} \quad \text{(17)}$$

The double-frequency terms represent a pulsating torque the net result of which is zero, integrated over a complete cycle.

Considering only the constant torque-component represented by the first four terms of Equation 17, the first three terms are always negative, since q is greater than 90°, and Q is less than 90°. According to my invention, I use enough lag-rings S to make $(Q-q)$ an angle whose cosine is positive by a quantity large enough to make the fourth term of Equation 17 approximately equal and opposite to the sum of the first three terms. This can easily be done by changing the number (or cross-section) of the shading-rings until the centering torque disappears or becomes negligibly small. In equation form, this relationship may be expressed,

$$K_6K_9\cos(Q-q)=-K_6K_8\cos(-q)-K_7K_8\cos(-Q-q)-K_7K_9\cos(-q) \quad \text{(18)}$$

Fig. 5 shows a complete induction-loop relay-element, designed with shading-loops S, as just described, to eliminate all but the pulsatory, or double-frequency, component of the "centering" bias-torque, so that the relay will be sensitive, as well as high-speed, high-torque, and compact. To illustrate the applicability of my relay to any directional element, which responds to the product of two fluxes, times a function of the angle between said fluxes, I have illustrated my Fig. 5 relay as being excited by two magnetizing-currents I_1 and I_2, which may be any two currents, or electrical quantities, simple or complex, of the same frequency, but of variable phase-relationships and/or magnitudes.

My relay is thus applicable to any directional-relay function, such as a differential relay, a wattmeter relay, an impedance relay, a directional relay, and many other types of functions which can be accomplished by obtaining the product of two alternating-current quantities multiplied by a function of the phase-angle between them. My relay is characterized by a minimum rotor-inertia and a large torque for its size, meaning a high speed of operation. It has a constant useful torque, even in a single-phase design, which ren-

ders it free from the evils of chattering. With the lag-ring feature, it also has a high sensitivity. Ample tests have proved the efficacy of my designs.

The relay-design shown in Fig. 5 is similar to that which has already been described for Fig. 2, except that the lag-rings S have been added to the leading and trailing pole-tips of each of the pole-pieces, as has been described in connection with Fig. 4. In Fig. 5, I have also indicated typical external phase-shifting impedances Z_c, Z_d, Z_m and Z_n, as described in connection with Figs. 1 and 2, although it will be understood that other phase-shifting means may be utilized, and also that the relay is of general application to the directional response to any two exciting-currents I_1 and I_2, however obtained or compounded.

I claim as my invention:

1. An alternating-current torque-producing device for directionally and differentially responding to two alternating relaying currents having the same frequency and having relative magnitudes and phase-relations which are subject to change, said device comprising a product-responsive element having two flux-producing winding-means for respectively producing two alternating magnetic fluxes, said fluxes being so cooperatively disposed as to produce a torque in response to the product of said two fluxes, multiplied by a function of the angle between them, and electrical means for so energizing said two flux-producing means that the respective fluxes are responsive to the respective relaying currents, and at least one of the fluxes is responsive also to the difference between the two relaying currents.

2. The invention as defined in claim 1, characterized by means for introducing a phase-shift in the relaying-current response of one of said fluxes, relative to the relaying-current response of the other flux.

3. The invention as defined in claim 1, characterized by means for introducing a substantially 90° phase-shift in the relaying-current response of one of said fluxes, relative to the relaying-current response of the other flux.

4. The invention as defined in claim 1, characterized by means for introducing a phase-shift in the relaying-current response of one of the fluxes, relative to the relaying-current response of the other flux, both of said fluxes being also responsive to the difference between the two relaying currents, and means for introducing a relative phase-shift between the two difference-current responses.

5. An alternating-current torque-producing device for directionally and differentially responding to two alternating relaying currents having the same frequency and having relative magnitudes and phase-relations which are subject to change, said device comprising a product-responsive element having two flux-producing winding-means for respectively producing two alternating magnetic fluxes, said fluxes being so cooperatively disposed as to produce a torque in response to the product of said two fluxes, multiplied by a function of the angle between them, and electrical means for so energizing said two flux-producing means that one of said fluxes is responsive to the sum of a response to the first relaying current and a response to the difference between the two relaying currents, and so that the other flux is responsive to the difference between a response to the second relaying current and a response to said difference between the two relaying currents.

6. The invention as defined in claim 5, characterized by means for introducing a phase-shift in the relaying-current responses of at least one of said fluxes, and means for introducing a phase-shift in the difference-current responses of at least one of said fluxes, whereby the two relaying-current responses have a relative phase-shift between them when the relaying currents are in phase, and the two difference-current responses have a relative phase-shift between them.

7. The invention as defined in claim 5, characterized by phase-shift means for causing the flux response to one of said relaying currents to be displaced from the flux-response to the other relaying current by approximately 90° when the two relaying currents are in phase, and phase-shift means for causing the differential-current flux-responses of the two fluxes to be shifted in opposite directions by approximately 45° with respect to the respective relaying-current responses of the respective fluxes when the two relaying currents are in phase, whereby the two difference-current responses are approximately 90° out of phase with each other.

8. The invention as defined in claim 5, characterized by the differential-current flux-responses being non-linear so as to have different proportionality-ratios at different values of the differential current.

9. A substantially non-vibratory alternating-current torque-producing device for directionally and differentially responding to two alternating relaying currents having the same frequency and having relative magnitudes and phase-relations which are subject to change, said device comprising a magnetizable field-member having four salient poles and electrical means for energizing said poles in diametrically opposite pairs in such manner as to cause said field-member to have two alternating magnetic fluxes flowing approximately in diameters at right angles to each other respectively, said electrical energizing-means being so responsive that the respective fluxes are responsive to the respective relaying currents, and at least one of the fluxes is responsive also to the difference between the two relaying currents, and a secondary rotor-member comprising two mechanically-connected-together loops normally lying in planes in substantial alignment with said fluxes, respectively, and mounted so as to have a slight oscillatory movement in response to the torques developed therein.

10. The invention as defined in claim 9, characterized by each pole having tip-mounted lagging means for causing the flux to lag in that portion of the pole.

11. A torque-producing electro-responsive device comprising means for providing a rotor-member having a coil having a coil-side in which an alternating current is induced, and a magnetizable stator-member having a salient pole-piece under which said coil-side is normally approximately centered, in torque-producing relation, alternating-current means for exciting said pole-piece, said pole-piece having tip-mounted lagging means for causing the flux to lag in that portion of the pole, and means for mounting said rotor-member so as to have a slight oscillatory movement in response to the torque developed therein, said rotor-member having only said single coil-side under said pole-piece, whereby said loop does not normally lie in the lagging-flux field of said tip-mounted lagging means, and whereby said tip-mounted lagging means operate as decentering means.

12. A loop-type torque-producing electro-re-

sponsive device comprising a rotor-member having a loop, and a plural-flux magnetizable stator-member having means for producing a plurality of fluxes therein, and alternating-current means for energizing said stator-member in such manner that it has an inducing alternating magnetic flux which threads through said loop in current-inducing relation thereto, and a torque-producing alternating magnetic flux in reacting relation to at least one coil-side of said loop, the flux-path of said torque-producing stator-member flux including a salient pole under which said coil-side is normally approximately centered, said salient pole having tip-mounted lagging means for causing the flux to lag in that portion of the pole, said rotor-member being mounted so as to have a slight oscillatory movement in response to the torque developed therein, said rotor-member having only said single coil-side under said pole-piece, whereby said loop does not normally lie in the lagging-flux field of said tip-mounted lagging means, and whereby said tip-mounted lagging means operate as decentering means.

13. A loop-type torque-producing electro-responsive device comprising a rotor-member having a loop, and a plural-flux magnetizable stator-member having means for producing a plurality of fluxes therein, and alternating-current means for energizing said stator-member in such manner that it has an inducing alternating magnetic flux which threads through said loop in current-inducing relation thereto, and a torque-producing alternating magnetic flux in reacting relation to both coil-sides of said loop, the flux-path of said torque-porducing stator-member flux including two salient poles in such positions that the respective coil-sides of the loop are normally approximately centered under the respective salient poles, each of said salient poles having lagging means on both the leading and trailing tips of said poles for causing the flux to lag in said tips, said rotor-member being mounted so as to have a slight oscillatory movement in response to the torque developed therein.

14. A torque-producing electro-responsive device comprising a magnetizable stator-member having four salient poles and alternating-current exciting-means for causing a first alternating magnetic flux to circulate through the first and third poles, and a second alternating magnetic flux to circulate through the second and fourth poles, each of said four poles having lagging means on both the leading and trailing tips of said poles for causing the flux to lag in said tips, and an induction rotor-member having a coil-side which is normally approximately centered under each of said four poles, said rotor-member being mounted so as to have a slight oscillatory movement in response to the torque developed therein.

15. A sensitive, substantially non-vibratory, induction-loop torque-producing electro-responsive device, comprising a magnetizable field-member having four salient poles and electrical means for energizing said poles in diametrically opposite pairs in such manner as to cause said field-member to have two diametrically flowing magnetic fluxes alternating at the same frequency and having relative magnitudes and phase-relations which are subject to change, said fluxes flowing approximately in diameters at right angles to each other respectively, and a secondary rotor-member comprising two mechanically-connected-together loops normally lying in planes in substantial alignment with said fluxes, respectively, and mounted so as to have a slight oscillatory movement in response to the torques developed therein, each of said four poles having lagging means on both the leading and trailing tips of said poles for causing the flux to lag in said tips.

16. The invention as defined in claim 15, characterized by an amount of tip-mounted lagging means sufficient to make $(Q-q)$ an angle whose cosine is positive by a quantity large enough to make the fourth term of the bias-torque-expression

$$\phi^2K_6K_8\cos(-q)+\phi^2K_7K_8\cos(-Q-q)+\phi^2K_7K_9\cos(-q)+\phi^2K_6K_9\cos(Q-q)$$

approximately equal and opposite to the sum of the first three terms, where $(-Q)$ is the angle of lag produced by the lagging means, $(-q)$ is the angle by which the induced current in either loop lags behind the inducing flux which threads through that loop, ϕ is the unshaded flux which traverses the central portion of any pole, and K_6, K_7, K_8 and K_9 are constants defining the inducing flux $[K_6\phi+K_7\phi\angle(-Q)]$ and the torque-producing flux $[K_8\phi+K_9\phi\angle(-Q)]$.

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