

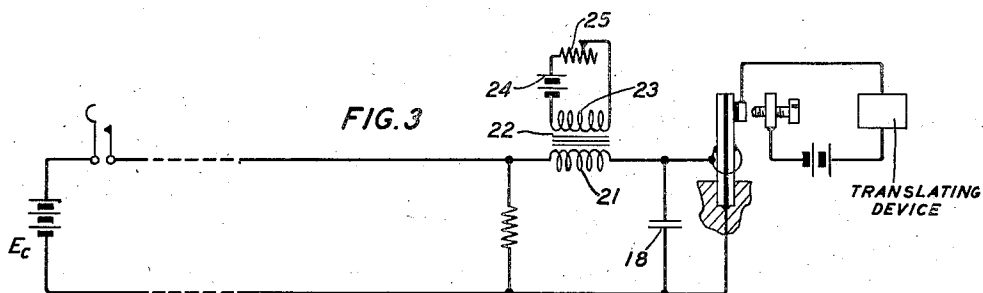
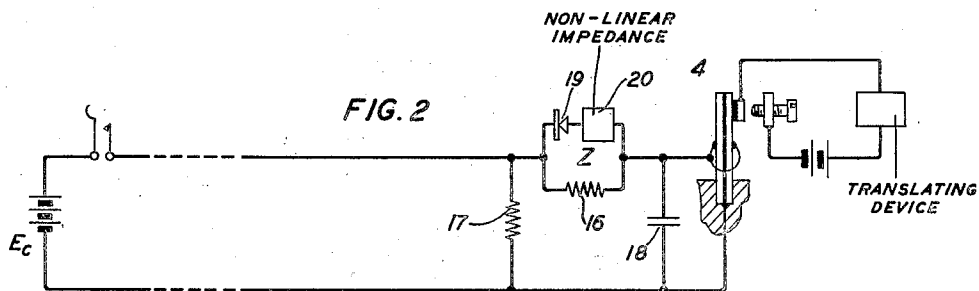
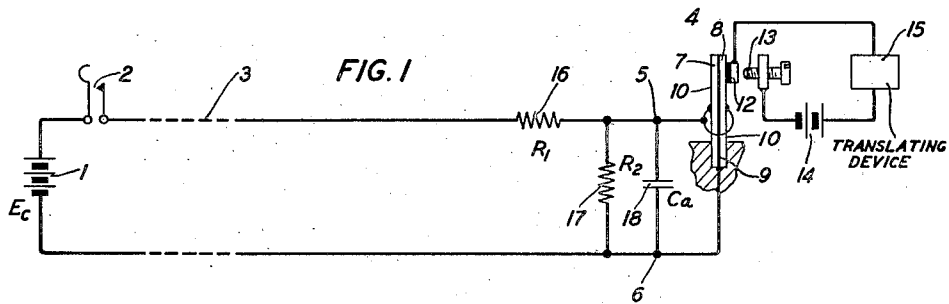
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D. G. BLATTNER ET AL

2,201,879

DELAY TYPE PIEZOELECTRIC REL

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## UNITED STATES PATENT OFFICE

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## DELAY TYPE PIEZOELECTRIC RELAY

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9 Claims. (Cl. 175—320)

This invention relates to delay type relays employing piezoelectric-actuated members.

An object of the invention is to provide means for determining the time required for a piezoelectric relay to operate after application of the actuating electromotive force to its circuit.

Another object is to provide means for determining the time required for piezoelectric relay to release after withdrawal of the actuating electromotive force from its circuit.

An additional object of the invention is to provide means for obtaining any desired operating time for a piezoelectric relay without interfering with its desired delay time in releasing and vice versa.

A further object of the invention is to enable the practicable range of ratio between the operating time and the release time of a piezoelectric relay to be substantially extended with respect to those hitherto attainable.

Piezoelectric relay structures and operating circuits suitable for such relays are disclosed in the U. S. Patent of W. P. Mason, No. 2,166,763 granted July 18, 1939, for Piezoelectric apparatus and circuits. Such relays may be characterized as electrostatic in that they are essentially capacity elements and they operate in response to a charge impressed upon their input terminals. They remain operated without further application of energy to the relay until such charge has been withdrawn or such an interval has elapsed that the charge has dissipated. Such relays present many very desirable features. Finite amounts of power are required to operate them but no power is required to hold them in the operated position. They may, moreover, be operated with moderate electromotive forces over circuits of extremely high impedance ranging in some cases in the order of megohms. This enables the use of such devices for remote control apparatus over long lines and in high resistance circuits.

Inasmuch as the piezoelectric relays are essentially capacitance elements the problem of their operation and release is fundamentally that of charging and discharging a condenser. It is, therefore, possible to so coordinate the relay with the charging and discharging circuit as to obtain various desirable operating characteristics and it is with such aspects of the piezoelectric relay problem that the present invention is concerned.

In accordance with this invention the charging source which may be at a point both geographically and electrically remote from the piezoelectric relay is connected through the input terminals of the relay to the capacity electrodes of

the piezoelectric element over a path which include a charge regulating impedance. This impedance is such that in conjunction with the capacity of the relay, supplemented in some instances by an auxiliary capacity element, the time within which the source will bring the potential across the relay to the necessary operating magnitude may be predetermined. In order to permit the relay to release at some desired interval after the source has been disconnected a discharge regulating impedance element of suitable type and magnitude is provided to cause the voltage across the relay to drop to its releasing value in a definite time interval.

The discharge path is naturally a shunt path across the line leading to the relay. If the charge regulating impedance be connected between the discharge regulating impedance and the relay, the discharge current must traverse the charging impedance and the discharging impedance in series provided the charge and discharge regulating impedances are symmetrical with respect to direction and magnitude of current. This imposes rather severe limitations in that for a given charge, the rate of discharge must always be less than the rate of charge and, therefore, the range of release times that can be had is limited. This disadvantage may be avoided by resort to a discharge path connected between the charge regulating resistance and the relay thereby making the release time independent of the operate time. This feature of the invention is not without a certain disadvantage in that during the charging operation the two impedances act as a potentiometer between the source and the relay and thus require a higher voltage source. As an alternative method of overcoming the release time limitation an additional feature of the present invention is provided in which the path including the charge regulating impedance is of an asymmetric character and is so designed as to have the proper impedance for charging current but a negligible or different impedance for discharge current.

Additional aspects and features of the invention will be apparent from a consideration of the detailed specification taken in connection with the accompanying drawing in which

Fig. 1 illustrates a piezoelectric relay circuit for permitting the magnitudes of the charging and discharging paths to be substantially independent of each other.

Fig. 2 illustrates a modification of the circuit in which an asymmetric impedance element is

connected between the discharge regulating impedance and the relay.

Fig. 3 discloses a circuit similar to that of Fig. 2 with an alternative type of asymmetric impedance element employing a saturated core inductance.

Referring to Fig. 1 there is illustrated a circuit including a source 1 of charging current of an electromotive force  $E_c$ , switch or circuit closer 2, a line 3 leading to a remote piezoelectric relay 4 having input terminals 5 and 6. The relay is illustrated diagrammatically as of the bilame or two-plate type disclosed in Mason Patent No. 2,166,763. As is explained in the specification of that patent, the plates 7 and 8 may be cut from Rochelle salt or other suitable piezoelectric material and may be glued or clamped to an intervening common electrode 9 which comprises a metallic or other conducting coating applied to each plate or to both. The two oppositely located outer faces of the piezoelectric plates are similarly conducting electrodes 10 and are electrically connected to terminal 5, the inner electrode 9 being connected to terminal 6. The plates 7 and 8 may be clamped or held firmly in contact at their lower ends by any suitable means to constitute a unitary assemblage.

The plates 7 and 8 are so cut that an electromotive force of proper polarity impressed between terminals 5 and 6 causes one plate to lengthen and the other to contract thus causing the assemblage to flex laterally to one side to carry the attached insulated contact element 12 into engagement with a stationary adjustable contact element 13 to close the circuit of local source 14 through the motor or other translating device 15.

Associated with the line 3 are the series charge controlling resistance 16 of magnitude  $R_1$  and the shunt discharge resistance 17 of magnitude  $R_2$ . There may also be connected across the terminals 5-6, an auxiliary or shunt capacity element 18, the magnitude of the capacity of which is  $C_a$ . The auxiliary capacity may be dispensed with in instances where the electrostatic capacity of the piezoelectric device between electrodes 9 and 10 is sufficiently large. Mason has also shown in his patent, No. 2,166,763, that under certain conditions it may be advantageous to connect an auxiliary capacity in series with the piezoelectric element as is illustrated in Fig. 11 of that application.

The operating time required after closure of the switch 2 to enable the relay 4 to close the contacts of its local circuit is determined by the time necessary to charge the capacitance of the piezoelectric relay up to its operating potential. Neglecting the potential drop in the line 3, the voltage across the relay  $t$  seconds after the switch 2 is closed is

$$(1) \quad E_{R_2} = \frac{Q}{C} = i_2 R_2$$

Where  $C$  represents the combined capacity of the condenser  $C_a$  and of the piezoelectric relay,  $Q$  is the charge at time  $t$  and  $i_2$  is the current through  $R_2$ . Therefore

$$(2) \quad i_2 = \frac{Q}{CR_2}$$

and

$$(3) \quad i_c = \frac{dQ}{dt}$$

where  $i_c$  is the current flowing into capacity  $C$ .

By Kirchhoff's electric circuit laws:

$$(4) \quad E_c = i_1 R_1 + i_2 R_2$$

and

$$(5) \quad i_1 = i_2 + i_c$$

Substituting the values of  $i_2$  and  $i_c$  in (5)

$$(6) \quad i_1 = \frac{Q}{CR_2} + \frac{dQ}{dt}$$

and substituting the value of  $i_1$  from Equation (6) and of  $i_2$  from Equation (2) in Equation (4)

$$(7) \quad E_c = R_1 \left( \frac{Q}{CR_2} + \frac{dQ}{dt} \right) + R_2 \frac{Q}{CR_2}$$

and

$$(8) \quad E_c = (R_1 + R_2) \frac{Q}{CR_2} + R_1 \frac{dQ}{dt}$$

which may be rewritten as:

$$(9) \quad \frac{dQ}{dt} + \frac{R_1 + R_2}{CR_1 R_2} Q = \frac{E_c}{R_1}$$

Let

$$\frac{R_1 + R_2}{CR_1 R_2} = K$$

and

$$\frac{E_c}{R_1} = k$$

Then Equation (9) becomes

$$\frac{dQ}{dt} + KQ = k$$

which may be solved for  $Q$  by multiplying both members by an integrating factor  $e^{Kt}$

$$(10) \quad e^{Kt} \frac{dQ}{dt} + e^{Kt} KQ = ke^{Kt}$$

The left-hand member of Equation (10) is the same as

$$\frac{d}{dt}(e^{Kt} Q)$$

so that (10) may be written as

$$(11) \quad \frac{d}{dt}(e^{Kt} Q) = ke^{Kt}$$

Integrating gives

$$(12) \quad e^{Kt} Q = \frac{k}{K} e^{Kt} + A$$

where  $A$  is a constant of integration to be evaluated later.

$$(13) \quad Q = \frac{k}{K} + \frac{A}{e^{Kt}}$$

Substituting the values of  $k$  and  $K$  in (13)

$$(14) \quad Q = \frac{E_c R_2 C}{R_1 + R_2} + \frac{A}{e^{\frac{R_1 + R_2}{R_1 R_2 C} t}}$$

or

$$(15) \quad Q = \frac{E_c R_2 C}{R_1 + R_2} + A e^{-\frac{R_1 + R_2}{R_1 R_2 C} t}$$

When

$$t=0 \quad Q=0 \quad \text{and} \quad A = -\frac{E_c R_2 C}{R_1 + R_2}$$

Substituting in (15)

$$(16) \quad Q = \frac{E_c R_2 C}{R_1 + R_2} - \frac{E_c R_2 C}{R_1 + R_2} e^{-\frac{R_1 + R_2}{R_1 R_2 C} t}$$

or

$$(17) \quad Q = \frac{E_c R_2 C}{R_1 + R_2} \left( 1 - e^{-\frac{R_1 + R_2}{R_1 R_2 C} t} \right)$$

but from

$$(1) \quad E_{R_2} = \frac{Q}{C}$$

$$(18) \quad E_{R_2} = \frac{R_2}{R_1 + R_2} \left( 1 - e^{-\frac{R_1 + R_2}{R_1 R_2 C} t} \right) E_c$$

When  $t$  is very large this voltage across the relay approaches the limiting value

$$(19) \quad E'_{R_2} = \frac{R_2}{R_1 + R_2} E_c$$

If the operating potential at which the piezo-electric relay flexes sufficiently to close the circuit with its contacts 12 and 13 be  $E_0$  (a value less than  $E'_{R_2}$ ) then  $T_0$ , the time required to cause the relay to operate after closure of the switch 2 is obtained by substituting  $E_0$  for  $E_{R_2}$  in Equation (18).

Thus

$$(20) \quad E_0 = E_c \frac{R_2}{R_1 + R_2} \left( 1 - e^{-\frac{R_1 + R_2}{R_1 R_2 C} T_0} \right)$$

from which

$$(21) \quad e^{-\frac{R_1 + R_2}{R_1 R_2 C} T_0} = 1 - \frac{E_0}{E_c \frac{R_2}{R_1 + R_2}}$$

and taking logarithms of both members

$$(22) \quad -\frac{R_1 + R_2}{R_1 R_2 C} T_0 = \log_e \left( 1 - \frac{E_0}{E_c \frac{R_2}{R_1 + R_2}} \right)$$

Solving for  $T_0$

$$(23) \quad T_0 = -\frac{R_1 R_2 C}{R_1 + R_2} \log_e \left( 1 - \frac{E_0}{E_c \frac{R_2}{R_1 + R_2}} \right)$$

or

$$(24) \quad T_0 = -\frac{R_1 R_2 C}{R_1 + R_2} \log_e \left( 1 - \frac{R_1 + R_2}{R_2} \frac{E_0}{E_c} \right)$$

When the switch 2 is opened the discharge circuit consists simply of condenser C discharging through resistance  $R_2$ . The condenser has a potential  $E_{R_2}$  given by Equation (18) and since  $E_0$  is the potential across the condenser or across  $R_2$  at which the relay will release the time of release  $T_r$  is the time required for the potential to drop from  $E_{R_2}$  to  $E_0$ . This relation between potential and time is well known. (See, for example, The Engineers' Manual by R. G. Hudson, 1st edition, page 207, section 879, John Wiley & Sons, Inc., copyright, 1917.) It is given by

$$(25) \quad E_0 = E_{R_2} e^{-\frac{T_r}{R_2 C}}$$

or

$$(26) \quad e^{-\frac{T_r}{R_2 C}} = \frac{E_0}{E_{R_2}}$$

taking logarithm of both members and solving for  $T_r$ .

$$(27) \quad T_r = R_2 C \log_e \frac{E_{R_2}}{E_0}$$

It will be noted that this expression for  $T_r$  does not involve the resistance  $R_1$ . It is, therefore, apparent that the release time may be predetermined by a suitable choice of the magnitudes of  $R_2$  and  $C$  irrespective of  $R_1$ . The operating time, although calculated from an expression involving  $R_2$ , may, in effect, be given any value desired by proper choice of  $R_1$  and of  $E_c$ , the electromotive force of source 1.

Fig. 2 discloses an alternative method of ob-

taining the advantage of Fig. 1 without its disadvantage. In this case the charge regulating impedance Z consisting of a resistance element 16 and an asymmetrical element 19, e. g., a copper oxide rectifier, is connected between the element 17 and the relay 4. The element 19 is so designed and poled that its impedance to charging currents is large in comparison with the impedance of 16 or in comparison with its own impedance to discharge currents. This enables relay 4 to be charged through element 16 from source 1 but to discharge through 19 and 17. The impedance of the discharge path may be of any desired value without regard to the impedance of the charging path and yet the full potential of source 1 is effective in charging which is to say the final steady state of potential across the capacity element 18 and the piezoelectric relay 4 is substantially equal to the charging electromotive force of source 1. Accordingly, through the use of this circuit the electromotive force of source 1 may be considerably reduced with respect to that required for the circuit of Fig. 1. This circuit, therefore, has the advantage which circuit 1 possesses of enabling the discharge or release time of the relay to be entirely independent of the operate time without the disadvantage of the high charging electromotive force for source 1 which the circuit of Fig. 1 entails. The circuit of Fig. 2 offers the additional possibility of employing a non-linear impedance element, the resistance of which is a function of the magnitude of the discharge current. Such a non-linear impedance may comprise a thyrite element 20 in series with the copper oxide rectifier 19. If the resistance of the element 20 be made an inverse function of the current, the discharging rate will be decreased as the steady state condition is approached and the release interval will be increased over that which may be obtained with a fixed resistance. In a similar manner the charging time may be increased by making the charge regulating resistance 16 also of thyrite.

The circuit of Fig. 3 is similar to that of Fig. 2 with the modification that the resistance and rectifier combination 16, 19 of Fig. 2 is replaced by an impedance 21 associated with a magnetic core 22 which may be magnetized to the saturation point by means of an associated coil 23 in circuit with a local source 24 and a rheostat 25. If the core 22 be substantially saturated the impedance coil 21 may serve to present low impedance to the charging current for the reason that the flux of the charging current is in the same direction as that produced by the polarizing current. Consequently since the core is saturated there is no energy required from the charging current for setting up flux in the impedance coil 21 and the coil therefore reacts as a negligible or at most very low impedance. Conversely, the flux produced by the charging current tends to oppose the polarizing flux and, accordingly, to increase the impedance of the coil 21. For very short intervals such as those involved in relay operation the impedance element may serve effectively as an asymmetric conductor.

It is evident, of course, that in both circuits 2 and 3 the effects of the asymmetric paths with respect to charging and discharging currents are reversible.

What is claimed is:

1. A piezoelectric relay, a charging source therefor, a charging circuit connecting the source to the input terminals of the relay and including a charge regulating impedance cooperating with

the electrostatic capacity of the relay to determine the operating time of the relay, a discharging circuit including a discharge regulating impedance and means connecting the discharging circuit to the relay input terminals to determine the time for release of the relay after withdrawal of the charging electromotive force said time being substantially independent of the magnitude of the charge regulating impedance.

2. A piezoelectric relay system including a charging circuit comprising a source of charging electromotive force, a charge regulating impedance and the input terminals of a piezoelectric relay all in series to determine the time for the relay to respond after application of the charging electromotive force, and a discharge path connected between the input terminals of the relay and including a discharge regulating impedance to determine the interval between the withdrawal of the charging electromotive force and the release of the relay, said interval being substantially independent of the magnitude of the charge regulating impedance.

3. A circuit for determining the operating and release periods of a piezoelectric relay comprising in series a source of electromotive force, a circuit closer, a first resistance element and the input terminals of the piezoelectric relay, a second resistance element connected in shunt discharge path at a point between the first resistance element on the one hand and the source of electromotive force and the circuit closer on the other, and an asymmetric conducting device connected in shunt to the first resistance element to freely pass discharge current from the relay around the first resistance element.

4. A piezoelectric relay, a charging source and means connecting the source to the relay comprising an impedance element the impedance of which is an inverse function of the current whereby the time required for the relay to be charged up to an actuating potential is increased over that which would be required were the impedance constant.

5. A piezoelectric relay, a discharge circuit therefor including a current regulating impedance having an effective value which is an inverse function of the discharging current to increase the time required for the deenergization of the relay after withdrawal of the source of actuating electromotive force.

6. A piezoelectric relay system comprising a piezoelectric relay having contacts operable into and out of engagement with each other, input terminals upon which actuating potentials may be impressed, a circuit including in series a source of actuating electromotive force, a circuit closer, an asymmetric current path and the input terminals whereby upon closure of the circuit closer an electromotive force is impressed upon the input terminals over the asymmetric path, and a shunt impedance element connected across the circuit between the asymmetric path and the circuit closer and source of electromotive force whereby upon opening of the circuit closer a charge impressed upon the input terminals may discharge over the asymmetric current path and the shunt impedance.

7. A piezoelectric device having input terminals, charging and discharging paths connected thereto and including in common an element which is asymmetrically conducting for transient currents of opposite polarity, the charging path including a source of charging electromotive force, the discharging path including a resistance element to determine the period for deenergization of the device after the charging electromotive force is withdrawn.

8. A piezoelectric relay system comprising a source of actuating electromotive force, a ferromagnetic impedance element and the input terminals of a piezoelectric relay all connected in series, a discharge path connected in shunt across the system at a point between the source and the impedance element, and means for establishing a polarizing magnetic field in the region of the impedance element whereby the element behaves in an asymmetric fashion in differentiating between sudden charging and discharging currents.

9. In a series circuit, a piezoelectric electromechanical device, a source of electromotive force, an asymmetric impedance element and a charging resistance element in shunt to the impedance element, a path in shunt to the electromechanical device including a discharging resistance element whereby a predetermined operating period and a predetermined release period for the electromechanical device may be provided.

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