Feb. 25, 1969 J. J. HORAN 3,430,080

PIEZO-ELECTRIC HIGH-VOLTAGE ALTERNATORS AND GENERATORS

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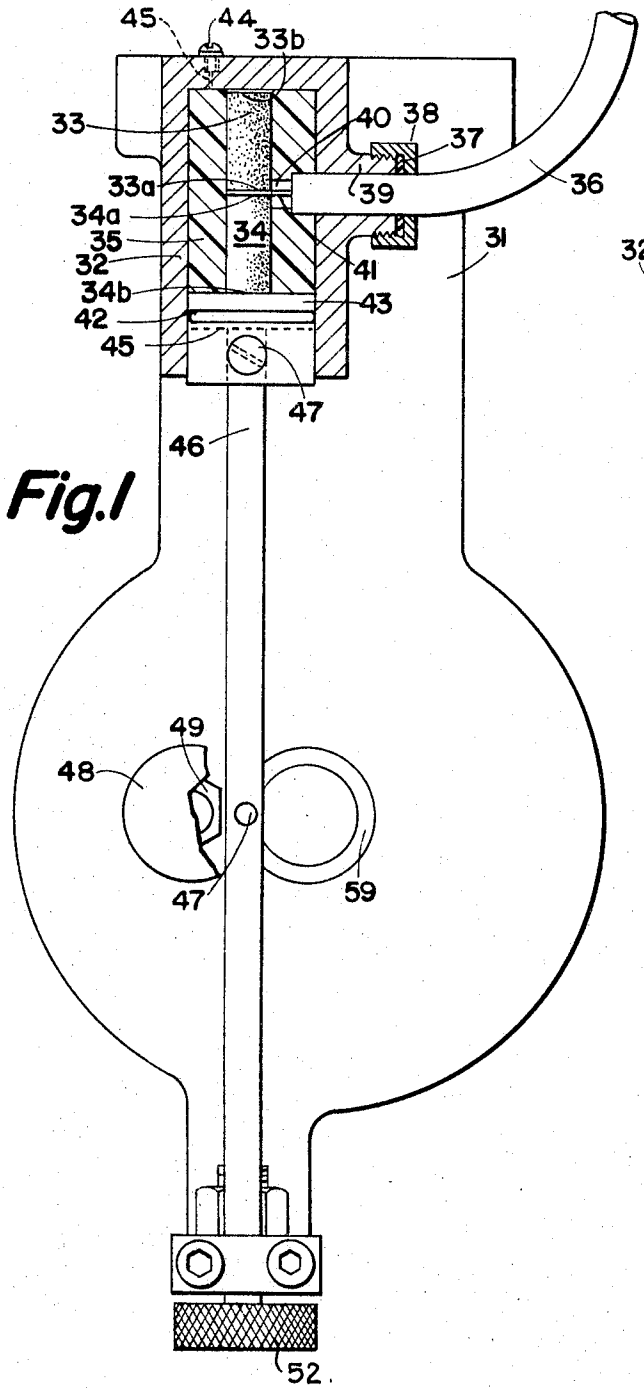


Fig.1

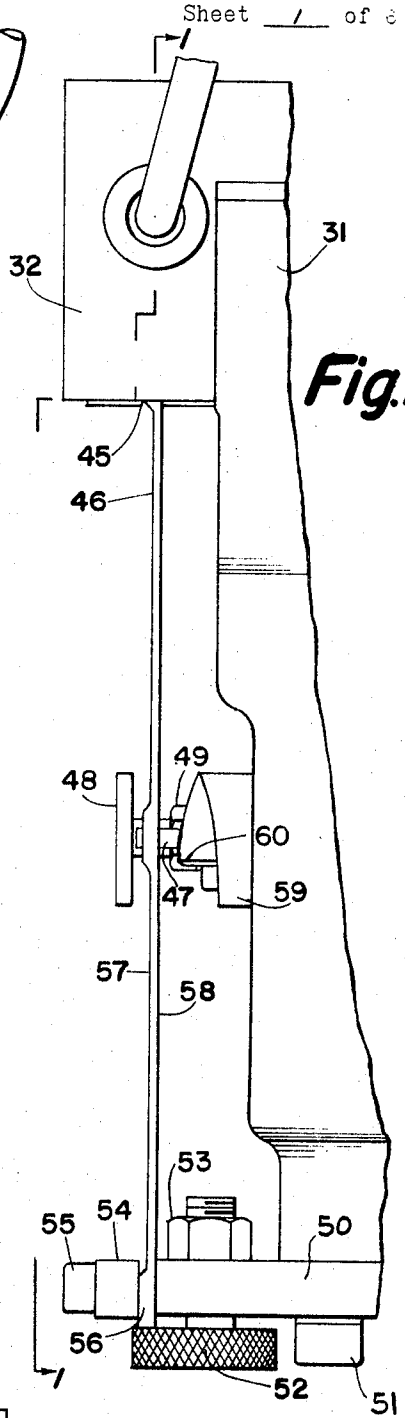


Fig.2

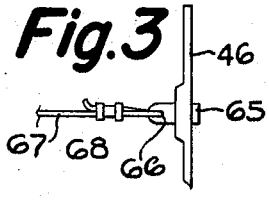


Fig.3

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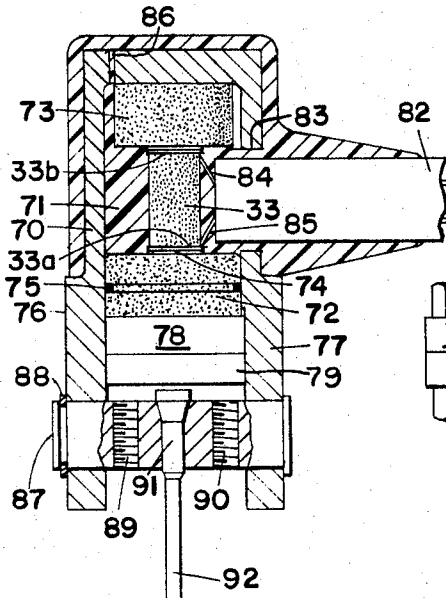


Fig.4

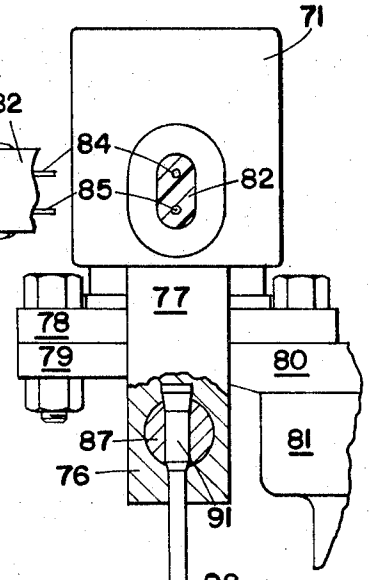


Fig.5

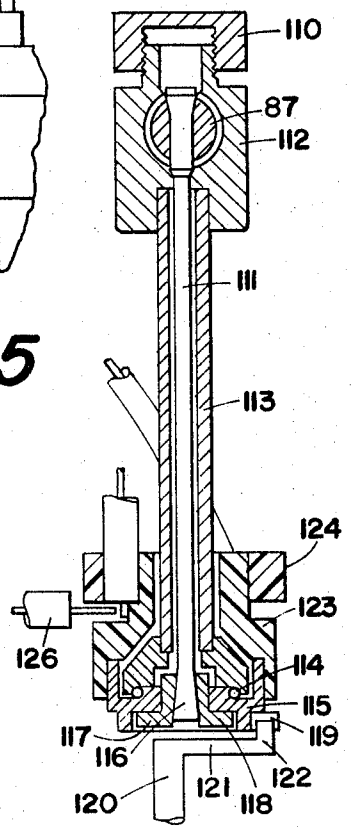
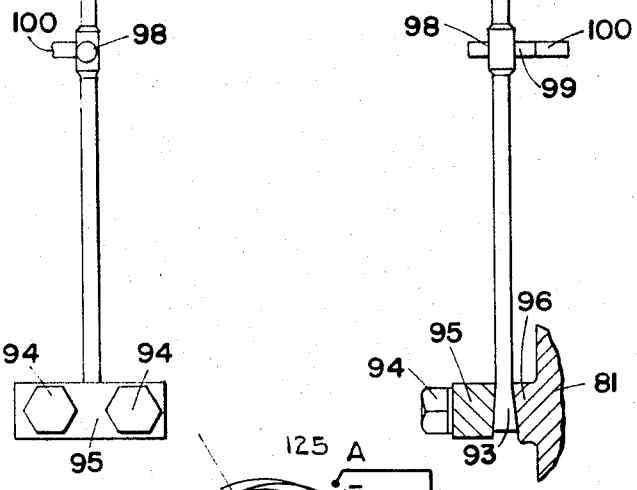


Fig.6



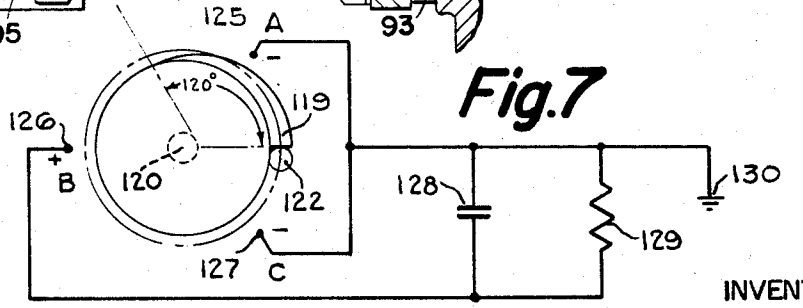


Fig.7

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Fig.8

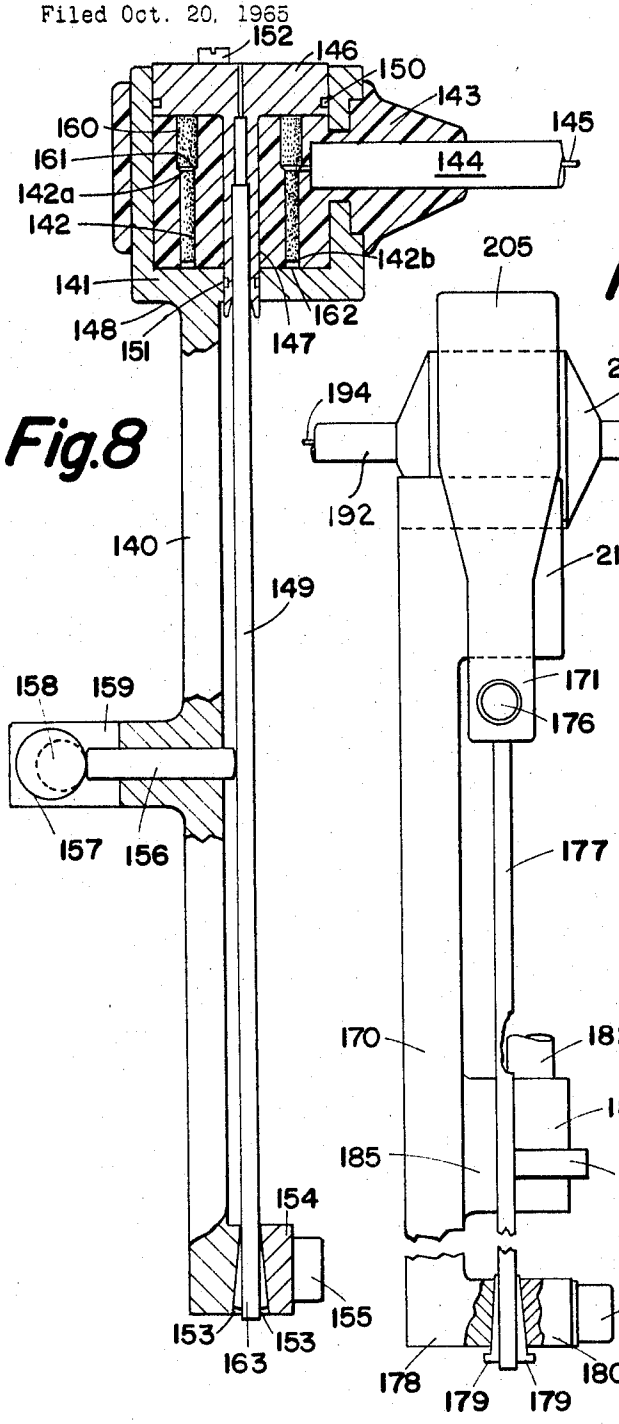
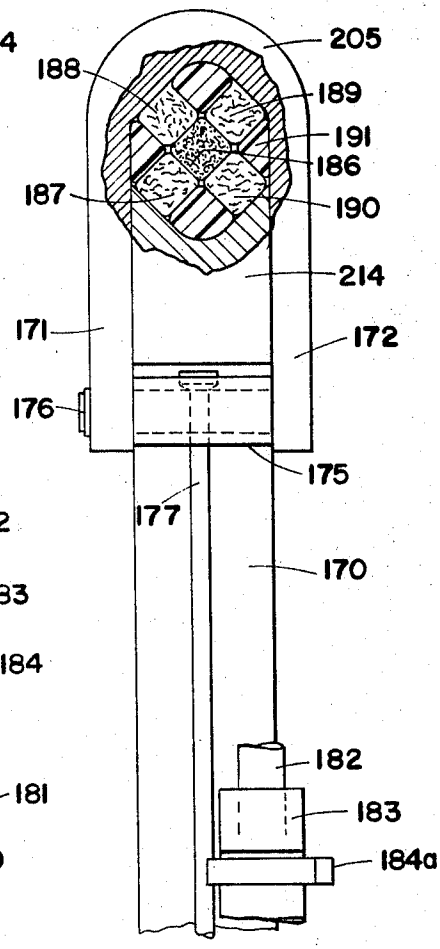


Fig.9

Fig.10



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Fig. 11

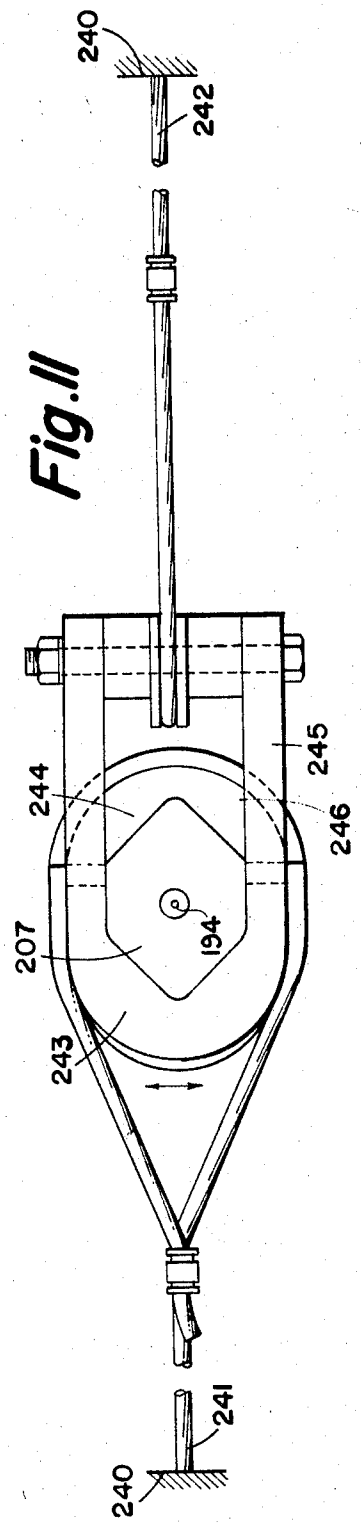
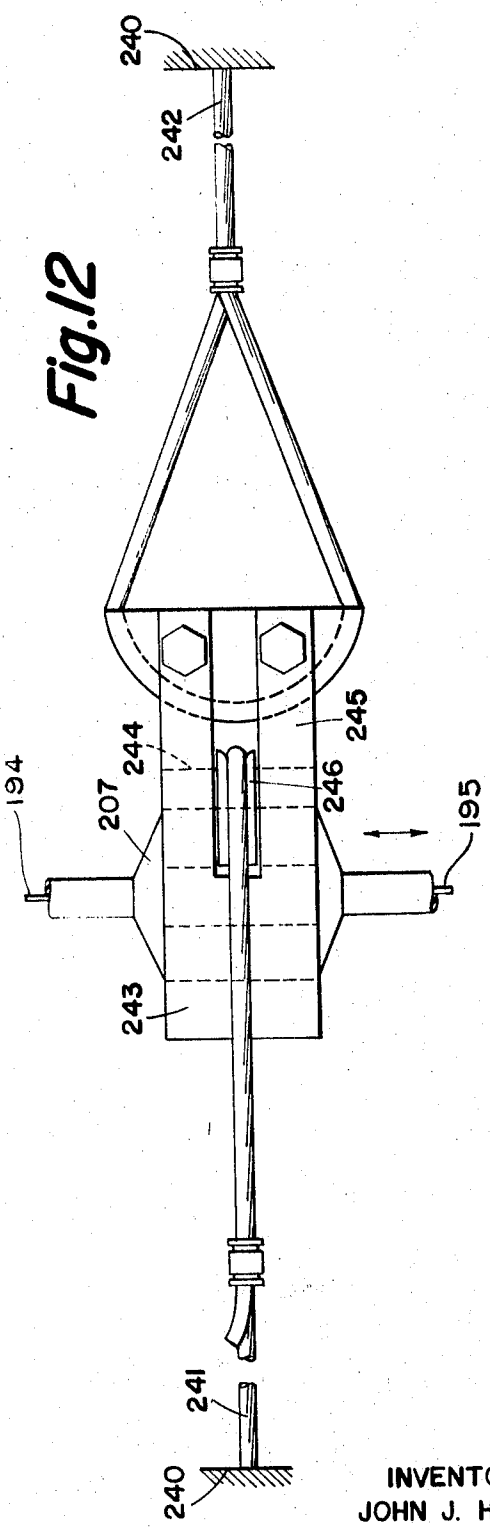


Fig. 12



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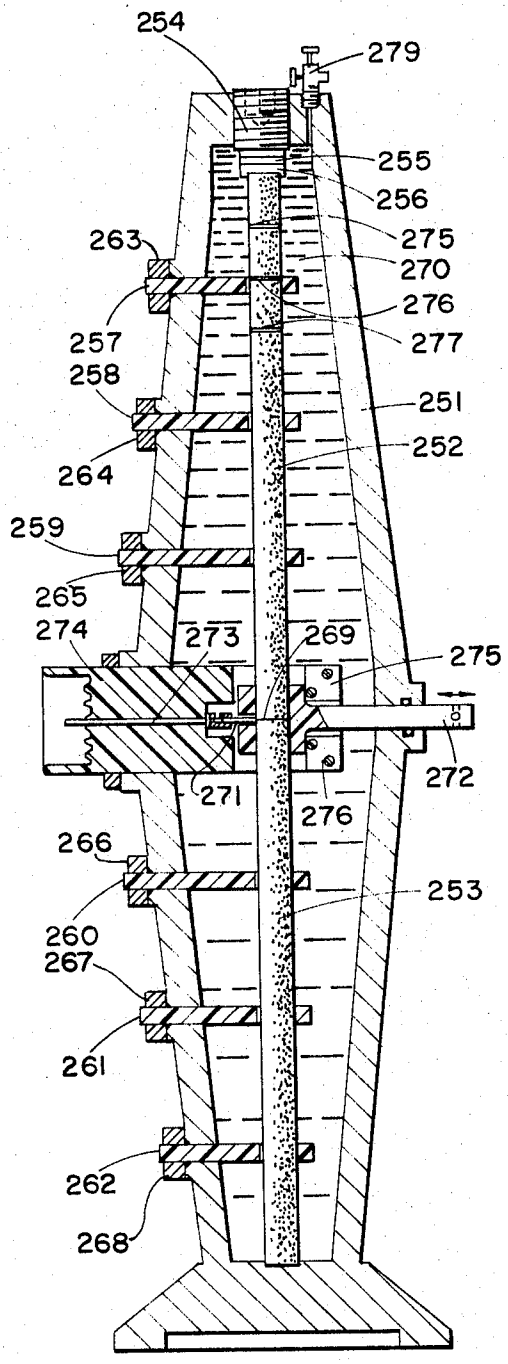


Fig. 13

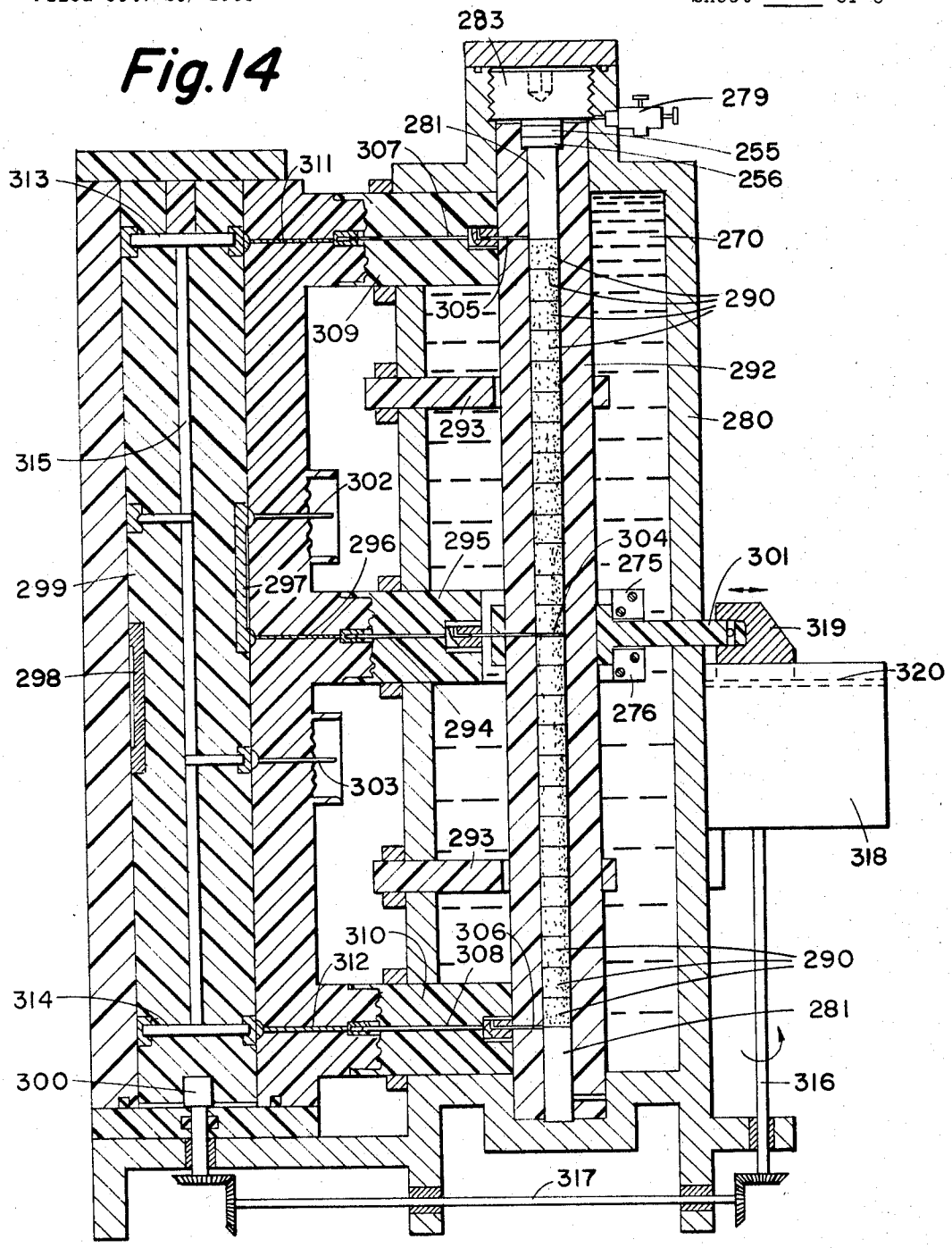
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PIEZO-ELECTRIC HIGH-VOLTAGE ALTERNATORS AND GENERATORS

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Fig. 14



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United States Patent Office 3,430,080
Patented Feb. 25, 1969

3,430,080

PIEZO-ELECTRIC HIGH-VOLTAGE ALTERNATORS AND GENERATORS

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Filed Oct. 20, 1965, Ser. No. 498,549
U.S. Cl. 310—8.7 20 Claims
Int. Cl. H02n 1/00, 11/00

ABSTRACT OF THE DISCLOSURE

High-voltage and very high-voltage piezo-electric alternators having elastic structure and intended for use in internal-combustion-engine ignition systems and elsewhere, together with direct current generators employing similar structure.

This invention relates principally to high-voltage piezo-electric alternators for use in ignition systems for internal-combustion engines and other applications and to high-voltage direct-current generators employing related mechanical structure, the active materials used being ceramic ferro-electrics.

It is an object of this invention to introduce an entirely new mode of action for piezo-electric alternators completely devoid of high-mechanical-pressure bearing points, which are difficult to adjust and subject to critical surface wear.

It is an object of this invention to disclose piezo-electric generating devices having a quiet mode of operation free of the racket produced by hammer and lever types.

It is an object of this invention to disclose piezo-electric generating devices in which both high-voltage electrodes are completely ungrounded.

It is an object of this invention to disclose a family of piezo-electric high-voltage direct-current generators based on simple forms of commutation applied to the alternators disclosed herein.

An object of this invention is to disclose piezo-electric high-voltage alternators and generators in which the maximum stress that can be applied to the element can be fixed in advance so that overtravel of the actuator will not overstress the element.

An object of this invention is to provide piezo-electric high-voltage generators having non-linear mechanical advantages between the actuator and the element which can be better tailored to requirements than can linear types.

An object of this invention is to provide piezo-electric high-voltage generators and alternators in which the loading of the element is self limited by the geometry of the loading means.

Other objects and novel features of this invention will be found in the balance of the specification, in the claims, and in the drawings, in which:

FIG. 1 is a partly cutaway illustration of one form of alternator of this invention adapted to fit the principal casting of a one-cylinder internal-combustion engine;

FIG. 2 is a view taken at a right angle to FIG. 1;

FIG. 3 is a fragmentary view showing a different actuator means for the device of FIGS. 1 and 2;

FIG. 4 is a partly cutaway illustration of a second form of this invention;

FIG. 5 is a partly cutaway view taken at a right angle to FIG. 4;

FIG. 6 is a cutaway view of an alternative actuator portion adapted to coact with the piezo-electric portion of FIGS. 4 and 5 and illustrating an arrangement for generating direct current;

FIG. 7 is a diagram illustrating schematically the commutation method of FIG. 6;

FIG. 8 is a partly cutaway illustration of a third major form of this invention;

FIG. 9 is a partly cutaway view of a fourth general form of this invention in which the load is applied to the piezo-electric element in a different manner;

FIG. 10 is a partly cutaway view taken at a right angle to FIG. 9;

FIG. 11 is a view of another major form of this invention;

FIG. 12 is a view taken at a right angle to FIG. 11.

FIG. 13 is a view of another major form of this invention, shown sectioned.

FIG. 14 is a view of still another major form in cross section.

Referring now to FIGS. 1 and 2, internal-combustion-engine casting **31** has a cast-in auxiliary chamber **32** bored out to accommodate cylinders **33** and **34**, made of a ferro-electric material, such as electrically polarized ceramic lead titanate zirconate. These cylinders **33**, **34** are piezo-electric, that is, when pressure is applied axially, the opposite ends of each will assume opposite electrical charges. Each cylinder **33**, **34** has its ends **33***a*, **33***b*, **34***a*, **34***b* coated with a conductive electrode material such as fired-on silver frit, which has been used in the polarizing process and is again to be used to gather and carry off the electrical charges when the cylinder is squeezed mechanically. Thes cylinders **33**, **34** are enclosed in a snugly fitting insulating cylinder **35**, preferably of an elastomer having good dielectric strength in order to withstand the high voltages developed between the opposite ends of each of the cylinders **33**, **34**. The letters *a* and *b* appended to the cylinder-end designations indicate polarity, **33***a* yielding the same polarity as does **34***a*, which may be considered by convention as positive upon squeeze and negative upon release of pressure. Opposite polarities will then appear at the opposite or grounded ends **33***b* and **34***b*, that is, negative upon squeeze and positive upon release. Thus, the cylinders together simultaneously generate two pulses per cycle of squeeze and release, the successive pulses being always of opposite polarity.

High-tension cable **36** has a molded-in flange **37**, held in place as a waterproof seal by nut **37**, threaded onto boss **39**. Cable **36** fits into a pre-molded opening in insulating cylinder **35**, squeezing out all remaining excess of the silicone grease **40** with which the boss **39** and chamber **32** are first filled. The projecting cable electrode **41** makes contact with live ungrounded electrode ends **33***a* and **34***a*.

Chamber **32** is sealed by elastomeric O-ring **42**, which fits in a groove engirdling thrust plug **43**. Sealing screw **44** closes vent **45** which has been provided as an exit for excess silicone grease so that the tightly fitting components may be installed in chamber **32** with a minimum of included air. Slot **45** in thrust plug **43** admits the end of actuating column **46**, which is locked in place in the plug **43** by set screw **47**.

Actuating column **46** is made of spring steel of a high hardness so that it will remain elastic under very high mechanical loads and deflections. Its ends and middle portion are slightly thicker than the remainder in which most of the flexing takes place. In order to provide the optimum balance between stiffness and load carrying ability, and in order to give absolute control over the plane of flexure without using auxiliary guides, the column is much wider (FIG. 1) than it is thick (FIG. 2). The column has a riveted-in wear pin **47** at its center. This wear pin **47** is prevented from being moved to the left, as seen in FIG. 2, by broad headed stop screw **48** which is threaded into casting **31** and locked in position by nut **49**.

Actuating column **46** is pre-loaded at the bottom. Arm assembly **50** is bolted to the bottom of the casting by

strong socket-head screws **51**. Pre-load adjusting screw **52** is locked in adjustment by nut **53**; and clamp **54**, locked in place by screws **55**, grips the thickened end **56** of column **46**. When so assembled and positioned, column **46** buckles away from stop screw **48** toward casting **31**.

Column **46** preferably has a length between its thickened ends that is very much greater than its minimum radius of gyration, which is measured from its axis in a direction perpendicular to one of the opposite flat sides, designated **57**, **58** in FIG. 2, ratios ranging from 50:1 all the way up to several hundred to one being in the appropriate range.

Column **46** in its preloaded condition is elastically buckled toward casting **31**. Its centrally located wear pin **47** is therefore thrust against and rides on the rim of cylindrical face cam **59**, a member which rotates in a clockwise direction as viewed in FIG. 1 and thus advances laterally, moving the wear pin. When the piston of an internal-combustion engine is traveling upward on its compression stroke prior to reaching firing position somewhat in advance of top dead-center position, the wear pin **47** will have advanced to the high position **60** of the cam **59** and elastically straightened the elastically buckled column **46**. It will have been observed from the foregoing description that the compressive load in the combined structural means composed of column **46**, the ferroelectric transducers **34**, and their supports consisting of thrust plug **43** and the inner portion at the upper end of chamber **32** is balanced by the tensile load in the endwise-coupled counter-structure of the engine casting **31**.

Because of the sin/cos relationship between the amplitude of transverse motion occurring at the wear pin and the very slight longitudinal motion taking place at the top of column **46** (the bottom end **56** being fixed) and the reciprocal relationship between the light force applied to the wear pin and the extremely high force developed at the top of column **46**, and applied via the plug **43** to the piezo-electric elements **33**, **34**, the force multiplication at the ends keeps increasing as the high position **60** of the cam is approached and as the formerly buckled column approaches maximum straightness. Very high forces (theoretically but not actually infinite) and, consequently, high voltages can be developed in the piezo-electric elements **33**, **34**, with only moderate values of applied forces at points that would otherwise be subject to wear or brinnelling, thus being distinguished from devices of the prior art; and no shock effect is suffered by the brittle piezo-electric. The voltage may be discharged via any extraneous timing device, such as those illustrated in a co-pending application.

When the face cam **59** rotates past the high point **60**, the spring forces existing in the elastically loaded column **46** and in the elements **33**, **34** are automatically released; and the wear pin **47** follows the drop-off of cam **59** and buckles once more. A voltage of opposite sign is developed in the elements **33**, **34** upon release of stress and awaits discharge by a suitable extraneous agency, as would be expected of these ferroelectric transducers.

Referring now to FIG. 3, the central fragment of the column **46** is seen, together with a pin **65** similar to the wear pin **47** of FIGS. 1 and 2, but having a drilled hole **66** therethrough. A cable **67** is threaded through the drilled hole **66** and secured therein by the squeeze fitting **68**. A cam, reciprocating link, an oscillating device or nutating member may be used to apply tensile forces and pull the column **46** leftward to the position shown and produce a voltage on the elements **33**, **34**. Motion that allows slack in the cable **67** permits the column **46** to move to the right towards its buckled position and relieve the peak stresses on elements **33**, **34**, which thereupon produce a release voltage of opposite sign, as before.

Referring now to FIG. 4, there is shown a cylindrical chamber **70** containing therein a cylindrical piezo-electric element **33**, identical to either of the elements in FIGS. 1 and 2. The element has its end electrodes **33***a*, **33***b* positioned between high strength, non-piezo-electric ceramic insulators **72**, **73** made of such materials as aluminum oxide or one of the electrical porcelains. Even when the abutting faces of all ceramics are finished to a high quality of parallelism and flatness, it is still often desirable to include at each of the ends very thin layers of stress-spreading material, such as stacked metal foil, designated here by numerals **74**. The ceramic insulator **72** at the open end of chamber **70** has a ground ring groove containing an O-ring **75**.

The chamber **70** terminates in opposite longitudinal extensions **76**, **77**, between which the thrust bar **78** is positioned. Thrust bar **78** may be combined integrally with mounting structure **79**, which in this case is an extension of cylinder head **80**, secured to engine cylinder **81**, or the thrust bar **78** may be bolted thereto as shown.

The ceramic insulators **72**, **73** make it possible to have both voltage leads ungrounded, a fact of which advantage is taken by bringing in a twin high-voltage cable **82**, via chamber opening **83**. The two electrical leads **84**, **85** emerging from the end of cable **82** are bent prior to insertion so that they will make contact with one of the layers **74** of the metal foil. When they are thus in position, the piezo-electric assembly is potted in place with an injection molding of elastomeric insulation **71**, preferably of such comparatively low-temperature-curing, high-dielectric-strength materials as the RTV silicones or the newer polyurethanes. Any such material is suitable as long as its injection and curing temperatures do not tend to depolarize the element. The injected material **71** carries entrained air out the vent **86** and is molded completely around the chamber **70** and part way up the cable **82**. It may be necessary to coat some of these materials beforehand with suitable primers.

A through hole is bored in order that extensions **76**, **77** may be linked by pin **87** which is held in place by retaining ring **88**. Tapped holes **89**, **90** permit the bolting of pull devices to pin **87**; but the principal showing is of an arrangement whereby the square shank **91** of torsional pull element **92** drops through a square-broached hole in rotatable pin **87**.

The torsional pull member **92** has a square cross section throughout most of its length. The bottom end is tapered **93**, permitting it to be gripped strongly by cap screw **94** tension, applied between clamp block **95** and the lower boss **96** on engine casting **81**.

Thus, it is seen that, with torsional pull member **92** firmly secured between pin **87** and boss **94**, there is a firm spatial relationship between the lower end of engine casting **81** and ceramic insulator **73** abutting the upper end of piezo-electric element **33**. A firm spatial relationship has also been shown between engine casting **81** and ceramic insulator **72** abutting the lower end of element **33**. Any shortening of torsional pull member **92** necessarily, therefore, applies a compressive loading upon element **33**.

Torsional pull member **92**, which has a square cross section, has swaged and bonded to itself at its middle a trunnion block **97** having extended pins **98**, **99**, the latter of which is aligned with thrusting pin **100**, other detail being eliminated for simplicity.

Thus, if thrusting pin **100** is moving to the right in FIG. 4 (coming up out of the paper in FIG. 5), it will cause trunnion pin **99** to be rotated at its middle portion with respect to both ends. Similarly, any object tending to move trunnion pin **98** to the left will also tend to rotate torsional pull member **92**. Obviously, a rotating collar adapted to catch trunnion pin **98**, **99** will also rotate torsional pull member **92**.

Any rotation of the middle portion of torsional pull member **92** with respect to its fixed ends will tend to foreshorten it. The same kind of motion-amplitude reduction and force amplification that was observed in column **46** of FIGS. 1, 2 and 3 takes place again in FIGS. 4 and 5, the amplitude being comparatively large and the torsional forces producing the moment at the center be-

ing small, and the applied force at the upper end being appropriately very great.

A very important advantage accruing from the electrical isolation of both ends of the piezo-electric element, as seen in FIGS. 4 and 5, is that, if the electrical output of the piezo-electric is fed into any commutating or rectifying device, the resultant output of the commutator or rectifier may have one side grounded without danger of short circuiting via any part of the structure seen in FIGS. 4 and 5.

Referring now to FIGS. 6 and 7, a new actuating portion has been designed, which is also capable of exerting an upward thrus via its adjustment nut **110** against ceramic insulator **72** of FIGS. 4 and 5, and thereby against the piezoelectric element **33**. The new actuating portion of FIGS. 6 and 7 is likewise adapted to exert a downward force via pin **87** against extensions **76** and **77** of FIGS. 4 and 5. Its torsional pull member **111**, like the prior torsional pull member **92**, is assembled when the pin **87** is rotated 90° out of position, after which the nut **110** is run all the way down upon column cap **112**, the pin **87** is rotated back into erect position, and adjustment nut **110** is jacked up into final position on its fine micrometer-type thread.

The stiff-column function, formerly performed by engine casting **81**, in FIGS. 4 and 5, is now assigned to a composite member consisting of adjustment nut **110**, column cap **112**, tube **113**, and upper bearing race **114**. The tensile forces are transmitted from extensions **76** and **77** of FIGS. 4 and 5, via pin **87** (loaded in bearing and shear) along torsional pull member **111**, which has a tapered lower end **116**, and into lower bearing race **115** locking wedges **117**, **118**.

Torsional pull member **111** may be twisted by rotating lower bearing race **115**, which has a laterally projecting lug **119**, intended for this purpose. So far, therefore, the device of FIG. 6 performs a function like that of the actuator portion of FIGS. 4 and 5.

Shaft **120**, driven by any convenient device, such as an electric motor or an accessory drive portion of an engine, rotates counter-clockwise (as viewed in FIG. 7) about its center, which is seen to be axially displaced from the centerline of torsional pull member **111** and its bearings **114**, **115**.

Shaft **120** carries, at the end of its arm **121**, a pin **122** which engages lug **119**. The centerline of the orbital path of pin **122** is described by the dot-dash line in FIG. 7 terminating in an arrowhead and pivoted around the center of shaft **120**. The path of lug **119**, which has a shorter arm length and which rotates about a different center, escapes from pin **120** after the lug **119** has traversed 120° of counter-clockwise travel. This travel winds up the torsional pull member **111** and foreshortens it slightly as occurred in FIGS. 4 and 5 with pull member **92**. When the pin **122** disengages from lug **119** after the latter has rotated 120°, the energy stored in the compressed piezo-electric and in the pull member **111** is released and the pull member **111** springs back to its original position. Meanwhile, shaft **120** continues to revolve until pin **122** again contacts lug **119** and the cycle begins again.

Lower bearing race **115** carries plastic block **123** to which the electrical leads issuing from the piezo-electric element **33** may be secured and held in place by plastic sleeve **124**. The positions in which the leads are located are 120° apart and are designated as A and B in FIG. 7. Three electrical receiver leads, **125**, **126** and **127**, pointing radially inward at 120° intervals, are mounted on any convenient structure. Only lead **126** of these latter 3 appears in FIG. 6. The other two leads are remotely joined as seen in FIG. 7, and connected to one side of condenser **128**, lead **126** being connected to the opposite side of the condenser **128**.

Remembering that electrical leads **84** and **85** in FIGS. 4 and 5 are both ungrounded, and remembering that the leads accumulate electrical charges of reversed sign every half cycle, it becomes clear that, if we adopt a 120° rotating excursion for the torsional pull member (or almost any convenient angular excursion) we can employ it as a switching means for the high-voltage current. Thus an electrical lead that changes sign from negative to positive as it moves from A to B of FIG. 7 (such as the remote end of lead **84** of FIGS. 4 and 5), will again reverse its sign from positive to negative upon returning to A. Also, if our second electrical lead, which would be the remote end of **85**, of opposite polarity, begins with a positive sign at B, it will have a negative signature when it arrives at C and will again become positive when it returns to B. Since the lead that arrives at C will always have the same negative polarity signature as the one which returns to A at the expiration of the next half cycle, we may interconnect C and A.

Therefore, we have a direct current generator capable of rapidly discharging increments of useful energy into condenser **128**, which in turn smooths these input increments to supply load resistor **129** with a relatively constant high-voltage direct-current input. Load resistor **129** may be any device requiring high potential at relatively moderate current drain rates such as an electrostatic air cleaner, wherein the fan motor drives the shaft **120** and no separate electronic power pack is required. As long as the piezo-electric element itself is ungrounded, it now becomes practicable to ground either side of the rectified or commutated high voltage supply, with no danger of short circuits arising between different sets of mechanical components mounted on a common chassis. The negative side is shown grounded at **130** for two reasons, which will not always be controlling: (1) by convention and (2) because of somewhat greater convenience and reliability results from grounding the side that has two contact points, A and C.

Referring now to FIG. 8, there is shown a heavy, eccentrically loaded column **140**, surmounted by an integral cylindrical chamber **141** containing a hollow cylindrical piezo-electric element **142** preferably potted in an insulating elastomer **143** which is sealably bonded to high-tension cable **144** containing electrical lead **145**. Element **142** has the customary fired-on silver electrodes **142*a*** and **142*b*** at its opposite ends, these ends being both seated on thin, stacked, metallic-foil stress-equalizing pads **161**, **162**.

Chamber **141** is closed at the upper end by metallic T-plug **146** having a hollow cylindrical stem **147** that extends down through the chamber **141** and its bottom wall **148**. A tension rod **149** of hardened spring steel is sweated for a considerable distance into the hollow stem **147** of T-plug **146**, in order to develop practically the full strength of the rod **149** in the joint thus made. The upper end of the chamber **141** is sealed by elastomeric O-ring **150** and the lower end by O-ring **151**. Temporary removal of sealing plug **152** permits completely filling the chamber **141** with elastomer **143** during molding or potting.

The lower end of tension rod **149** is sweat bonded to wedges **153**, **153**, which in turn are gripped between the lower end of column **140** and clamp block **154**, which is secured by a pair of socket-head screws **155**. Tension rod **149** may be deflected by moving pin **156** to the right, thus inducing an axial tension load in rod **149** that is many times greater than the relatively small transverse load applied to pin **156**. This deflection may be cyclically applied by any of several means, such as by eccentric cam **157**, which rotates on the end of shaft **158** (shown dotted), which in turn rides in a hole drilled through column spur **159** in line with the axis of pin **156**.

The load developed in tension rod **149** by the oscillating motion of pin **156** passes through the brazed joint to the stem **147** and thence via the large-diameter portion of T-plug **146** to ceramic insulating cylinder **160**, which thereby is forced alternately to compress and release cylindrical piezo-electric element **142**, one side of which is

grounded via electrode **142***b* and pad **162** to the bottom **148**. The "live" electrode **142***a* is contacted by electrical lead **145** which passes out of chamber **141** via high-tension cable **144**.

Referring now to FIGS. 9 and 10, there is shown a C-shaped eccentrically loaded but very stiff column **170**, arranged to have its upper arm **214** move relatively upward with extremely slight amplitude between the flanks **171**, **172** of a yoke **205** to compress a completely pre-molded, self-contained, water-proof piezo-electric assembly **207**, adapted to be inserted and removed as a unit from the mechanical components.

In order to be able to compress the piezo-electric assembly **207**, the yoke **205** is coupled via sleeve **175** and pin **176** to tensile member **177** which extends down to the foot **178** of the column **170**. The lower end of tensile member **177** is sweat brazed to wedges **179**, **179**, which are held against foot **178** by clamp block **180**, secured in place by socket-head screws **181**.

Shaft **182**, which turns in sleeve **183** that is a part of column **170**, drives cam wheel **184**, having a toe **184***a*, aligned to cyclically deflect tensile member **177**. As the toe **184***a* runs off the tensile member **177**, the member **177** snaps back into its original unstressed position.

The self-contained piezo-electric assembly **207** consists of centrally positioned piezo-electric element **186** having an oblong cross section, four non-piezo-electric ceramic pieces **187**, **188**, **189** and **190**, a mutual bonding and encapsulating elastomer **191** of high dielectric strength and relatively high adhesive properties, into which two cable ends **192** and **193** have been molded. The electrically conductive wires **194**, **195** within cable ends **192** and **193** respectively are in contact with the fired-on silver electrodes **196**, **197** (not seen) on the free ends of element **186**.

The encapsulating material **191** does not cover the outwardly exposed faces of the insulating ceramic pieces **187**, **188**, **189** and **190**, which mechanically contact the yoke **205** and upper end **214** of the column **170**. These faces and all inwardly turned parallel faces of these pieces which contact the element **186**, as well as the abutting faces of element **186**, are ground smooth, flat and parallel in order that optimum load distribution, with minimum stress concentration, will take place in these five relatively brittle pieces.

Deflection of tensile member **177** shortens it, causing the upper end **214** of column **170** to thrust upwardly against the bottom ceramic pieces **187** and **190**, which, together with pieces **188**, **189** and element **186**, are squeezed against the arched portion of yoke **205**. Although element **186** has been polarized in a direction other than that of the applied squeeze, it will, nevertheless, respond by developing voltages of the usual opposite signs on application and release of squeeze.

Referring now to FIGS. 11 and 12, there is shown another piezo-electric alternator. The device has a strongback **240** of any suitable configuration, represented here schematically, to which the ends of cables **241** and **242** are secured and adjusted to be tautly held in tension. The tension member consists of the high-strength steel cables **241**, **242** that imprison the previously described piezo-electric assembly **207** between a pair of V-blocks **243**, **244**, which in turn are part of yoke **245** and anvil **244** respectively. Application of tension to the yoke-anvil-cable assembly via the strongback **240** applies a tension to the cables **241**, **242** and compression to the element **186** hidden within the waterproof elastomer-sealed piezo-electric assembly. A simply way of applying tension and thus activating the piezo-electric element **186** within piezo-electric assembly **207** is to push the assembly in any direction perpendicular to the cable centerline. Releasing it causes a second electrical pulse of opposite polarity, as is characteristic of these ferroelectric transducers.

Oscillatory movement of the elastomer-sealed piezo-electric assembly in either direction indicated by either of the double arrowheads of FIGS. 11 and 12, by means similar to or comparable to those illustrated in prior figures, and, in fact, virtually any kind of movement in any desired direction will cyclically increase and decrease the pressure of the V-blocks against the element **186** within and cause it to generate a cyclical voltage successively displaying opposite signs in the electrical leads **194** and **195**.

Referring now to FIG. 13, there is seen a closed hollow frame, **251**, somewhat barrel shaped because of the higher electrical potential level existing at the middle, containing two polarized elongated ferroelectric ceramic elements **252**, **253**, extending from top to bottom therewithin. They are abutted in the middle so as to constitute one continuous column. Normally, the grounded ends will have a common polarity, the midpoint ends carrying the opposite sign.

The column of two elements is held under compression by pressure adjusting screw **254**, shown here at the top, with thrust bearing **255** and thrust washer **256** intervening. Any other suitable adjustment means may be substituted, such as a pair of sliding wedges. To keep this elongated column vertical and to control its tendency toward random buckling under compression, insulating guides **257**, **258**, **259**, **260**, **261**, **262**, which may be of ceramic or plastic, are provided at spaced intervals as one of a number of kinds of suitable guiding means. These guides have been aligned and adjusted so that, when the apparatus is in the position shown, the elements **252**, **253** will stand at the right-hand limit of travel in their slots in the guides. Although the clearance in each guide to the left of the column appears to be very small, for the scale employed it will often constitute an exaggeration.

Each guide has a locking member **263**, **264**, **265**, **266**, **267**, **268**, respectively, which may be of any convenient design suitable for maintaining the position adjustment of the guide and sealing against leakage of the contained dielectric fluid **270** via the opening in the frame for the stem portion of such guide. If the stem is cylindrical, the locking member may be internally threaded to match one on the stem; if it is of oblong or other cross section, suitable fasteners will be used. The sealing means may take the form of a wedge as shown or any other suitable form.

The ferroelectric column may be fairly long, up to 10 feet or more if desired. Thus, when the compressed column of two abutted elements **252**, **253** is permitted to buckle away from the right hand side of the slots in the guides **257–262**, an extremely high potential, which can extend into the multi-megavolt range and has a sign opposite that created when the column compression is increased, appears at the midpoint junction **269** between elements **252** and **253**.

It is not necessary that both elements **252** and **253** be polarized ferroelectrics. The same open-circuit potential can be developed even though one of them may be a non-ferroelectric member capable of insulating the voltage existing at the junction, but only half as much energy will be available for delivery. Thus, for example, the non-ferroelectric member may be of another ceramic, or it may be of composite ceremic-metal structure. If either end of frame **251** is made non-conducting, one of the elements may be inverted, in which case the open-circuit voltage will be doubled. However, as shown in FIG. 13, and first described above, the high voltage is most conveniently and reliably handled at the midpoint junction.

The entire cavity surrounding elements **252**, **253** is filled with a fluid of high dielectric strength such as a silicone liquid **270**. To keep the amount of gas or air within at a minimum (when the fluid is a liquid), valve **279** is used to apply a vacuum thereto before final adjustment of screw **254**, more liquid thereafter being admitted to exclude entry of air from outside.

Leading from midpoint junction is lateral pin electrode **271** which extends to the left via a clearance opening in actuator **272**. Since actuator **272** and the midpoint junction **269** are both moveable, lateral pin electrode **271** slides within a vented hole in the heavy end of stationary pin electrode **273**. Stationary pin electrode passes out of frame **251** via insulating block **274** which isolates the high potential from the frame and makes it available for coupling to a loading device.

Ferroelectric elements **252, 253** are held at their midpoints within actuator **272**, which is stopped at the right-hand limit of its travel by filler blocks **275, 276** of insulating material, which are bolted to the right end of insulating block **274**.

The clearance available in block **274** for lateral movement of actuator **272** is not large. Yet, because of the sin/cos force/motion-relationship between the lateral buckling of the column at its midpoint and the axial excursion at its ends, the amount of column foreshortening due to buckling is only a tiny fraction of the lateral motion. In fact the columnar excursion is scarcely observable except as a slight springing or change in stress of the frame **251**. The forces involved, however, have a ratio that is the approximate reciprocal of the motions.

Whenever the length/diameter ratio of the column is too great, the possibility exists that more than one mode of buckling may occur. For this reason, a plurality of insulating guides **257–262** has been shown. It may even become necessary to restrain the ceramic column even more carefully and to actuate its deflection from more than one point along its length. Were we to utilize actuators having no play where we now show guides **259, 260**, for example, it would be desirable to control the movement of such actuators at a level of approximately ¾ that of actuator **272**.

When ferroelectrics **252, 253** are made long enough to permit generating potentials on the order of megavolts, their manufacture presents problems. For one thing, the operating voltage that must be applied end to end for polarizing it is many times the voltage to be gained from its use. Since the process of polarization accomplishes some work, the end-to-end polarization voltage can not be described as an open-circuit voltage because an appreciable current must flow. Thus, if the entire element were to be polarized at once, the required generator would have to be a very substantial piece of equipment. In addition, even if the generator were available, the hazard of catastrophic breakdown, accompanied by violent shattering of the element at such high polarization potential, forces us to seek an alternate expedient.

Elements **253** and **252** can be polarized axially in stages if, in addition to the fired-on silver-frit electrodes we apply to the end surfaces, we apply ring electrodes **275, 276, 277**, etc., as circumferential rings of similar silver frit at regular intervals along its length. Such intervals, though seemingly more widely spaced (for illustration) in FIG. 13, preferably will not exceed about an inch, each ring being only wide enough to accept a temporary connecting wire for the polarization process. Then the first polarization step will be between the unseen end electrode under thrust washer **256** as the negative, while electrode **275** will be connected to the plus side. When the first end increment of the element has been polarized, electrode **275** is connected to the negative side of the polarizer and electrode **276** to the plus side. Thus, electrode **276** will have been polarized at two increments above ground potential. When this step is repeated again with electrode **276** now at negative and electrode **277** positive, the latter will be at three increments above ground, and so on via all electrodes along the entire length of element **252** until the opposite end electrode is reached, element **253** being electroded in the same manner. Polarization is somewhat more effective if two increments along the rod are polarized at the same time, with a voltage appropriate to their spacing, while the process is advanced only one increment at a time, each increment between electrodes thus feeling the polarizing potential twice. After polarization has been completed, the electrodes may, if desired, be removed with a reagent or an abrasive as seen in FIG. 13, except for electrodes **275, 276**, and **277**, which remain for illustration. Such removal is not necessary unless desired for some purpose such as reducing the possibility of partial arcover where the dielectric fluid may be contaminated or omitted.

As shown in FIG. 13, actuator **272** will be reciprocated only a very small distance, the stroke being approximately equal to the clearance seen between actuator **272** and the sectioned portion of insulating block **274**. Actuator **272** is shown with a pair of holes drilled at mutual right angles near its small end **278**, by means of which it may be coupled to a reciprocating drive. It will be found that the force required to reciprocate actuator **272** so as to generate very high voltages will actually be surprisingly light because of the tremendous mechanical advantage inherent in the geometry of the apparatus and the high efficiency common to the low-friction apparatus and the transduction process in the ferroelectrics.

Referring now to FIG. 14, the apparatus portrayed is functionally similar to that of FIG. 13. The differences lie in the fact that, instead of having only one or two long ceramic elements, the apparatus of FIG. 14 carries many small polarized ferroelectric cylinders, such as **290, 290, 290**, etc., all end-electroded and on the order of perhaps an inch long, no element being directly grounded in FIG. 14, thus adapting it to supply D.C. to a load as seen in FIG. 7.

The elements above the midpoint may, by choice, have their negative (as polarized) ends upward, their positive ends then being aligned downward toward the midpoint of the apparatus **304**. Those elements **290, 290**, etc., below the midpoint **304** would have their positive ends upward. Thus electrically we may have the same situation existing in FIG. 13. The short elements **290**, etc., are contained in an insulating tube **292** which preferably should have an inside diameter only large enough to permit the elements to be moved down its length, aided by the presence of silicone fluid **270** with which this apparatus is likewise filled. The material of tube **292** preferably will have a much lower modulus of elasticity than that of the ferroelectric in elements **290**, such materials as nylon being useful. Other means for containing and aligning elements **290**, etc., may be employed.

Adjusting screw **283** will usually require more turns than did adjusting screw **254** in order to apply the same compressive load to the ferroelectric column because of minor unevennesses existing on the end surfaces of the elements **290**, etc. For this reason it is usually desirable that foil leaves be inserted between the ends of the successive elements **290**, etc., in order to reduce the possibility of fracture of one or more elements caused by stress concentrations resulting from abutment of uneven ends. The use of foil will also squeeze out the liquid while making a more effective contact between the adjacent electrodes.

Because the resulting columns of short segments will be less stiff than the column of FIG. 13, the working clearance seen to the left of actuator **301** is likely to be greater than in the prior instance, resulting in a longer and softer stroke than that of actuator **272** in FIG. 13. The close fit and fairly heavy wall thickness preferred for tube **292** helps to counter the tendency for the column of elements **290**, etc., to buckle at multiple points. Insulating guides **293** may also have greater clearance for actuator stroke; but the clearance is again shown somewhat exaggerated for most applications.

The alternator portion of the apparatus of FIG. 14, like that of FIG. 13, is readily adapted also to be used as a high-voltage direct-current supply. One means of providing mechanical rectification is shown. Stationary pin electrode **294** leading out through insulating block

295, is commutated via lead-in electrode 296 alternately to bus 297 and bus 298 which are carried by rotating insulator 299 180° apart. Rotating insulator 299 is driven by imbedded shaft 300, which is powered by a common source to synchronize with the completion of each reciprocating stroke of actuator 301. When actuator 301 has moved to the left, bus 298 will rotate into contact with both electrodes 296 and 303; and on the next half revolution, bus 297 will return to position across electrodes 296 and 302, while actuator 301 has moved back to the right. The load will be connected across electrodes 302 and 303, which will generally carry a shunted storage capacitor. Either electrode 302 or electrode 303 may be connected to the grounded side of a capacitor bank and load circuit like that in FIG. 7, schematically, though the voltages may be orders of magnitude higher.

Ceramic insulators 281 located at both ends of the ferroelectric column of elements 290 separate and insulate the elements 290 from contact with the grounded frame 280, the arrangement differing from that of FIG. 13 in that neither end of the column of FIG. 14 is grounded. The column of elements 290 has greater clearance from frame 280 than did the upper and lower ends of the elements of FIG. 13, because these ends now will alternate with the middle junction 304 in carrying a high potential with respect to ground whenever the output of the rectifier on the left is connected to a condenser bank and load grounded as in FIG. 7. The arrangement of FIG. 13 could have been similarly adapted.

Pin electrodes 305 and 306, leading out respectively from the upper and lower ends of the column via holes in the walls of tube 292, make contact with the large ends of vented pin electrodes 307 and 308, carried by insulating blocks 309 and 310 respectively. Pin electrodes 307 and 308 terminate in the vented large ends of lead-in electrodes 311 and 312 respectively, each of which, twice each revolution of rotating insulator 299, makes contact with one of the 180°-separated shoes on the ends of cross pins 313 and 314. Cross pins 313 and 314 in turn make common contact with long bus 315, which alternately dumps its charge via electrodes 302 and 303 into whatever load may be connected to them, alternating in this respect with buses 297 and 298.

The drive for imbedded shaft 300 and rotating insulator 299 is via bevel-geared shafts 316 and 317, which are rotated by drive 318 in synchronism with reciprocating strokes of actuator 301, which has been fitted into block 319, which rides on crosshead 320, shown dotted.

Thus millions of volts DC, as well as AC, may be obtained from the AC-generating ferroelectric transducers of this invention.

Alternatively, it is possible to have switching means in only one leg of the circuit, as, for example, in the line leading from stationary pin electrode 294 only and not in either of the lines that communicate with long bus 315 in FIG. 14. In such event, both top and bottom ends of the stack of elements 290 would be connected to a line which may be appropriately connected to ground (as were the top and bottom respectively of elements 252 and 253 of FIG. 13). Ground would then float midway between a pair of capacitor banks in the line leading between ground and electrodes 302 and 303. It is, of course, possible to use only a single capacitor and avoid a ground tap completely.

It is obvious that various combinations can be made of the above inventive features, without departing from the true scope of this invention, which will be apparent to those skilled in the art. Obviously also, major improvements over the old art can be realized by adoption of only portions of the inventive feaures shown or of readily inferrable equivalents. It is, therefore, intended to include in the claims such portions and equivalents as may fall within the true scope of my invention. My invention is not to be limited to the specific forms or arrangements to which I have limited my descriptions, drawings, and claims for the sake of brevity and expeditious prosecution.

Therefore, I claim:

1. An apparatus for generating alternating voltage charges comprising:
- a polarized ferroelectric transducer;
- a pair of supports for said transducer positioned against opposite surfaces thereof;
- elongated structural means having therein a compressive load,
- said transducer and supports together constituting at least part of said means;
- elongated counter-structural means coupled endwise to said first means and having therein a tensile load in opposition to said compressive load,
- one of said means including a longitudinal portion that is elastically yieldable longitudinally responsive to elastic deflection thereof in a plane generally perpendicular to the load in said one means,
- said portion being distinguished by the storage of deflection energy recoverably therein as a function of said elastic deflection thereof; and a movable actuating member,
- said member being operably aligned for elastically deflecting said portion in said plane

whereby the magnitude of the load on said transducer may be varied.

2. An apparatus as in claim 1, wherein the said longitudinal portion is in tension.

3. An apparatus as in claim 1, wherein the said longitudinal portion is in compression.

4. An apparatus as in claim 3, wherein said transducer is an elongated column of longitudinally polarized ferroelectric material.

5. An apparatus as in claim 4, wherein said longitudinal portion is an elongated column abutted to said transducer.

6. An apparatus as in claim 4, said elongated column being contained within a tubular insulating structure.

7. An apparatus as in claim 1, including an adjustment for varying said loads.

8. An apparatus as in claim 1, including an adjustment for varying the position of said member.

9. An apparatus as in claim 1, said member being aligned for deflecting said longitudinal portion in torsion.

10. An apparatus as in claim 1, said member being aligned for deflecting said longitudinal portion in bending.

11. An apparatus as in claim 1,
- said longitudinal portion being unsegmented.

12. An apparatus as in claim 1, said transducer having conductively electroded surfaces at opposite ends thereof, said surfaces being aligned in a direction parallel to said load.

13. An apparatus for generating electrical potential comprising:
- a column of longitudinally polarized ferroelectric material having electroded surfaces at opposite ends thereof,
- said column having an axis therethrough;
- an insulated conductor leading from at least one of said electroded surfaces;
- a relatively non-conducting block abutting said surface;
- a frame having opposed restraining surfaces compressing said column and said relatively non-conducting block longitudinally therebetween,
- said frame including means for adjusting the position of one of the said restraining surfaces,
- thereby changing the magnitude of compression upon said column;
- a close-fitting insulating sleeve surrounding said column,
- said sleeve being composed of material having a lower modulus of elasticity than does said ferroelectric material;
- guide means positioned to restrain said sleeve against excessive lateral movement thereof;

and a thrusting mechanism adapted to deflect said sleeve and said column cyclically within the range of deflection permitted by said guide means,

thereby varying the magnitude of elastic buckling of said column and the electrical potential available between said electroded surfaces.

14. An apparatus as in claim **13**, said blocking constituting a second ferroelectric column endwise to the first-mentioned column of ferroelectric material.

15. An apparatus as in claim **13**, said column constituting a plurality of comparatively short pieces of said ferroelectric material stacked end-on-end and having electroded ends therebetween.

16. An apparatus as in claim **1**, said transducer having conductivity electroded surfaces at opposite ends thereof,

said apparatus having at least one insulated conductor communicating electrically between one of said electroded surfaces and a switching contact,

said switching contact being mechanically driven in cyclical synchronism with said member to make alternating momentary contacts with opposite termini of an extraneous electrical load circuit coincident with termination of each said excursion.

17. A direct-current generating apparatus comprising:

a relatively stiff frame having opposed restraining surfaces,

one of said surfaces exerting restraint toward one end of a stress member against motion of said end in at least one direction;

a ferroelectric transducer having an axis of polarization, to the ends of said transducer in which said axis terminates having conductive surfaces applied thereon,

said transducer being interposed between the second restraining surface and the second end of said stress member;

a cyclically actuated device for successively applying compression to said transducer and releasing said compression so as to stimulate a cyclically corresponding alternating voltage output therefrom via said conductive surfaces,

said transducer having at least one insulated conductor electrically joining one of said conductive surfaces with a switching contact;

and electrical switching means synchronized with said cyclically actuated device to create, coincident with said application and release of compression, alternating momentary junctions between said contact and one of two output termini adapted to feed an extraneous load,

whereby the polarity applied to such termini does not alternate with the output of the transducer.

18. An apparatus for generating alternating voltage comprising:

a stress member having a longitudinal axis therethrough,

the length of said stress member being greater by at least an order of magnitude than the minimum radius of gyration thereof perpendicular to said axis;

a relatively stiff frame having two separated restraining surfaces,

one of said surfaces exerting restraint toward one end of said stress member against relative axial motion thereof in at least one direction;

a polarized ferroelectric transducer compressively positioned to impose restraint between the second restraining surface and the second end of said stress member,

said transducer having conductively electroded surfaces at opposite ends thereof;

at least one insulated conductor communicating electrically with one of said surfaces;

housing means included in at least one of said frame and said stress member,

said housing means enclosing said transducer,

said housing means containing insulation therein adequate to isolate the voltage developed in said transducer;

an accessory device positioned to exert cyclically a relatively light, elastically deforming force against said stress member in a non-axial direction for a relatively long excursion,

an inverse force/motion relationship residing in said stress member as a function of the above-described disparity between said length and radius of gyration thereof,

a much lesser axial excursion being produced in said stress member and a much greater axial force being developed therein,

said axial force being co-exerted cyclically by said stress member and said frame upon said compressively positioned transducer

and stimulating a cyclically corresponding voltage output therefrom.

19. An apparatus for generating alternating voltages comprising:

a polarized piezo-electric transducer;

a pair of supports for said transducer positioned against opposite surfaces thereof;

elongated structural means having therein a compressive load,

said transducer and supports together constituting at least part of said means;

elongated counterstructural means coupled endwise to said first means and having therein a tensile load in opposition to said compressive load,

one of said means including an elastic longitudinal portion free from curvilinear longitudinally camming joints therewithin,

said portion being elastically changeable in length responsive to elastically flexible deflection thereof in a plane generally perpendicular to the load in said one means;

and a movable actuating member,

said member being operably aligned for elastically deflecting said portion in said plane,

the resultant change of load in said transducer being imposed by the longitudinal component of the elastic deflection of said portion,

whereby the magnitude of the load on said transducer may be varied without loss of energy via sliding friction of rotating joints in said portion.

20. An apparatus as in claim **19**,

said deflecting portion being segmented.

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U.S. Cl. X.R.

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