

Sept. 15, 1959

S. A. COLGATE

2,904,701

ELECTRICAL GENERATOR AND DRIVING ENGINE UNITARY THEREWITH

Filed June 7, 1957

3 Sheets-Sheet 1

FIG. 1

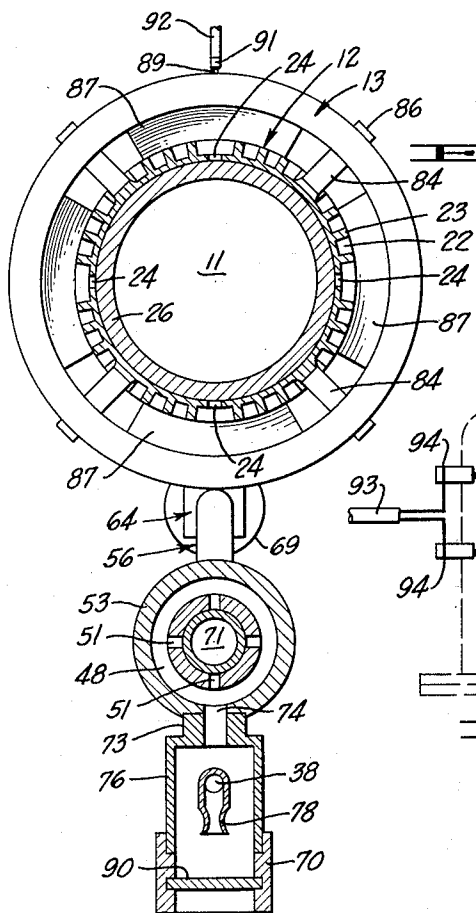
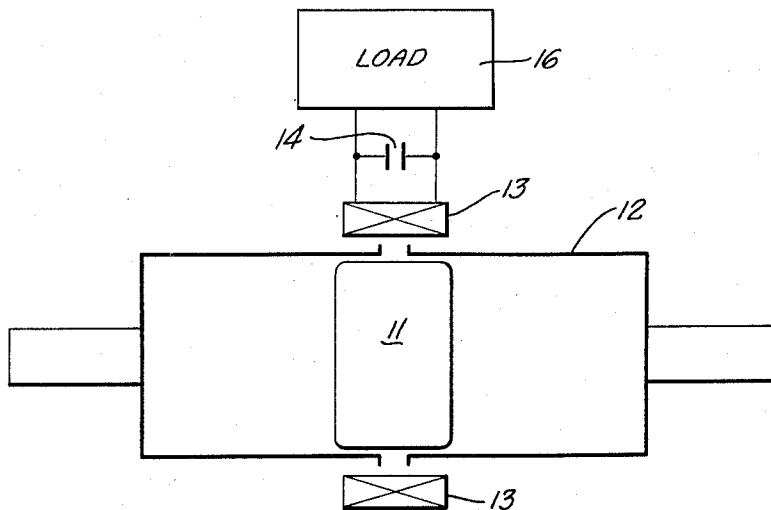


FIG. 4

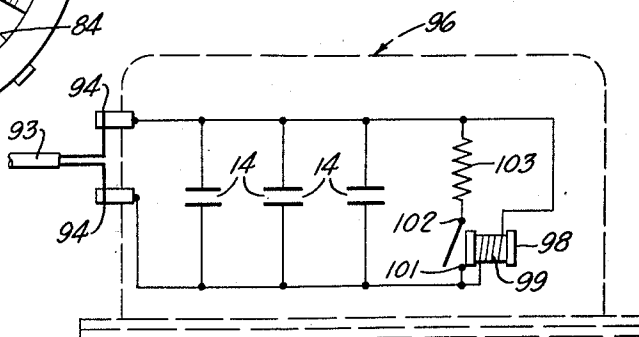


FIG. 5

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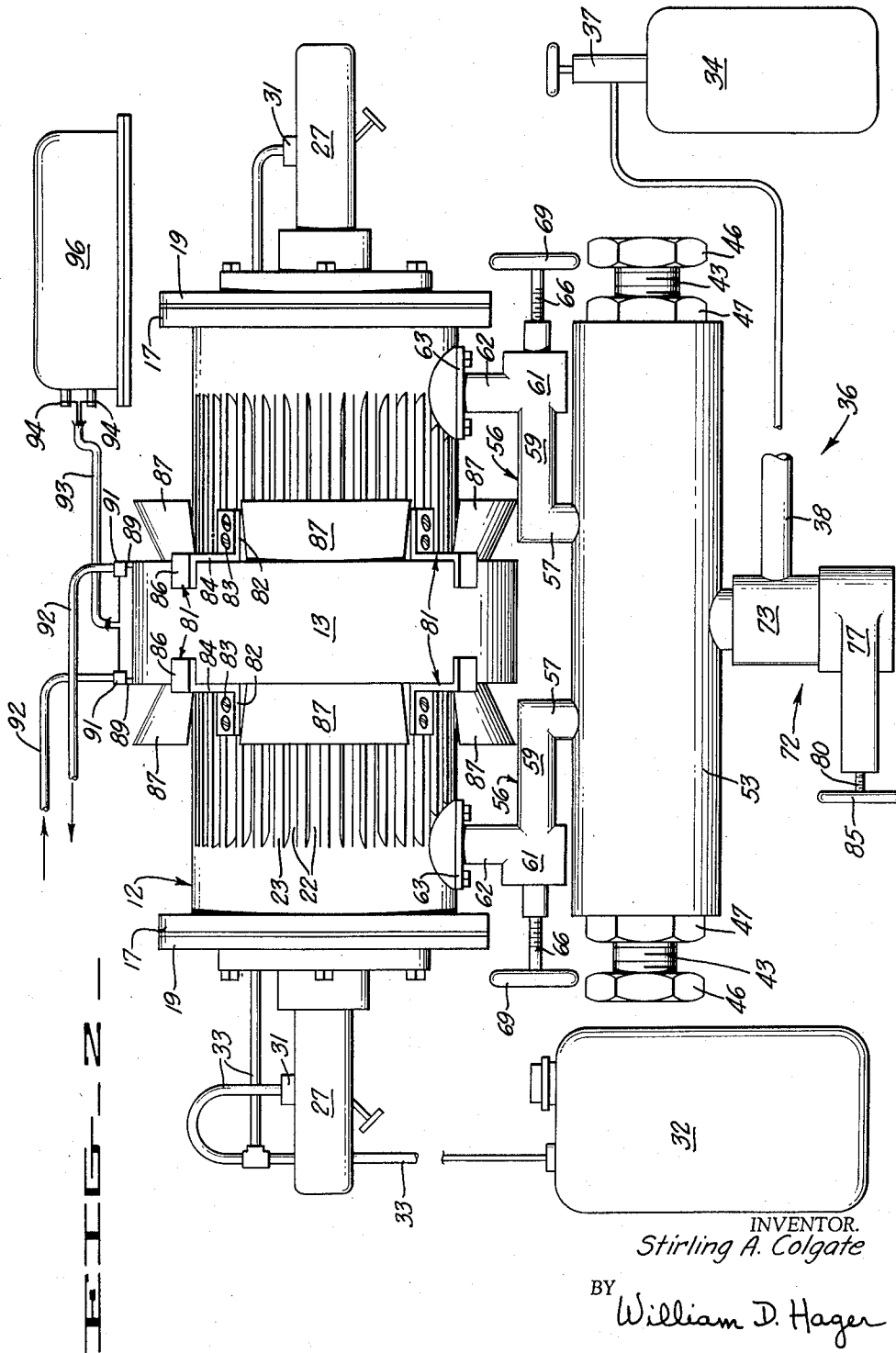
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3 Sheets-Sheet 2



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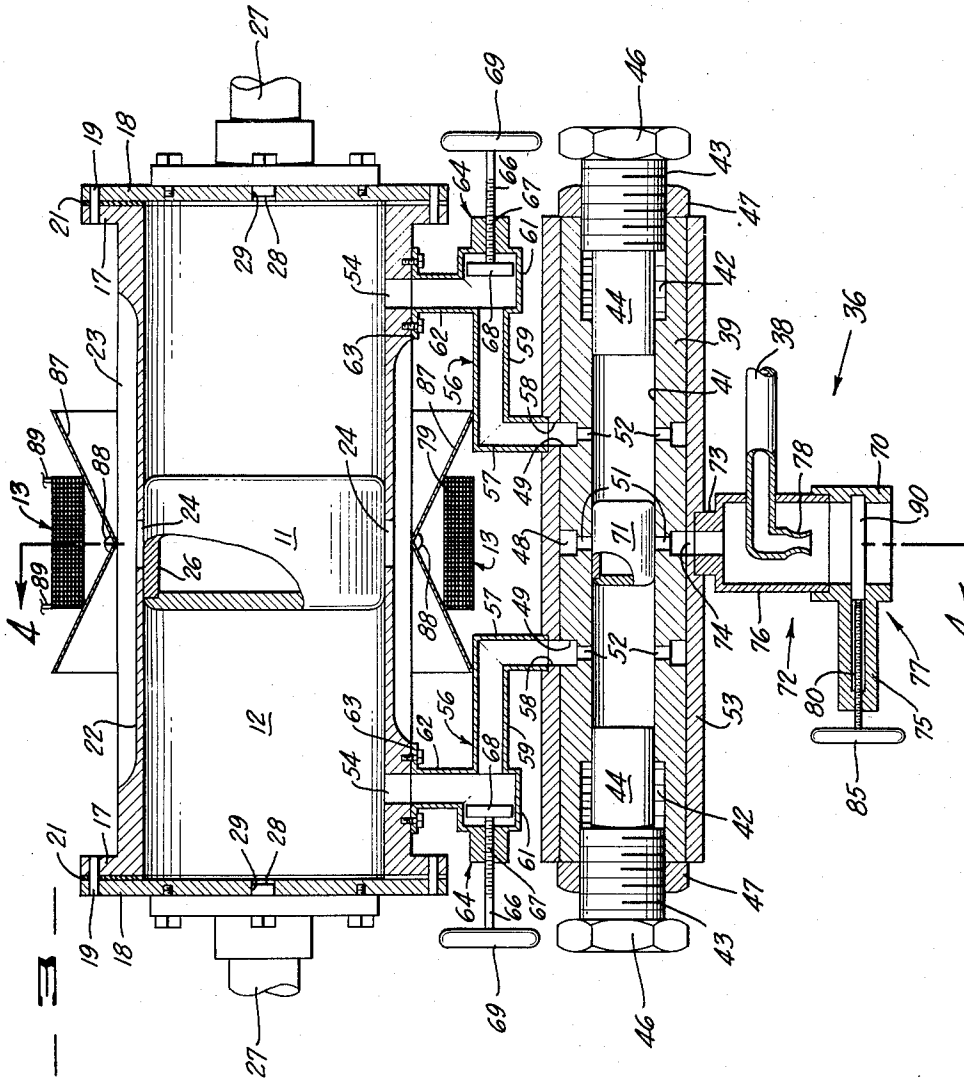
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3 Sheets-Sheet 3



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## ELECTRICAL GENERATOR AND DRIVING ENGINE UNITARY THEREWITH

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Application June 7, 1957, Serial No. 664,255

23 Claims. (Cl. 290—1)

The present invention relates to the production of electrical energy and more particularly to a compact highly efficient power generator, the invention further including a novel free piston engine which is advantageously combined with said generator as a unitary mechanism therewith for the purpose of driving the generator.

Apparatus for the generation of electrical power in commercially usable amounts has heretofore comprised two more or less separable and distinct mechanisms, a driving engine and the electrical generator proper. The driving engine may variously be a steam turbine, hydraulic turbine, or an internal combustion engine, as the particular situation and type of installation dictate. The generator unit, however, is almost invariably a mechanism of the class wherein a rotor assembly is turned at high velocity within an annular stator assembly. A consequence of the use of two essentially distinct mechanisms, the engine and the generator, is an excessive degree of bulk, weight, and complexity in relation to the power delivered. The latter undesirable factor is further compounded by the intricate structure of the conventional rotary generator.

As is apparent from the foregoing, considerable advantage is to be gained by reducing the size and complexity of the engine generator apparatus without, however, reducing the power output or efficiency. Aside from the obvious advantages of compactness and light weight, a reduction of installation cost and maintenance cost may be brought about.

The present invention achieves the foregoing by a radically new structure operating under unique principles. This invention relates to the adaptation of such principles to reciprocating systems, the use of the same in rotary electrical equipment being disclosed and claimed in a co-pending application of the present inventor entitled, Solenoid Stator Dynamo Electric Machines, Serial No. 721,144, filed March 13, 1958. Specifically the invention makes use of the ability of a reciprocating piston to transfer energy to a coil-capacitor circuit where the piston reciprocates in the magnetic field of the coil at a frequency corresponding to the resonant frequency of the circuit. While such energy transfer may be effected through the use of a ferromagnetic piston, it has been found advantageous to use a piston formed of non-magnetic material, the nature of the energy transfer thereby being entirely different. In the case of a ferromagnetic piston, it is necessary that such piston be either solid or at least have a wall thickness exceeding one-half the cross sectional area of the piston since the magnetic field must penetrate and flow through the piston. The result, however, is an extremely heavy piston which is thereby limited in velocity which in turn limits the electrical frequency which can be generated. A piston of this weight, for example, could not easily be driven at the standard sixty cycles per second. The effect of a non-magnetic piston, however, is to compress the magnetic field rather than to serve as a conductor for it, providing that the piston has a wall thickness approaching the magnetic skin

2

depth at the frequency of operation. As this wall thickness is relatively small, approximately one fourth inch for an aluminum piston operating at sixty cycles per second, the weight of the piston need not be great and high frequency reciprocation is easily accomplished.

As will hereinafter be discussed in detail, the energy transfer from the piston to the resonant circuit arises from the tendency of a conductor to exclude an oscillating magnetic or electrical field, such effect arising from the interaction of eddy currents induced in the conductor with the applied field. The distance which the applied field effectively penetrates the conductor is termed the skin depth which parameter decreases as the frequency of the field is increased. In most electrical machinery the principles of operation demand the field penetrate so that metal parts are either laminated, i.e. transformer iron, or copper conductors which are made less than a skin depth thick as in the case of hollow high power transmission line cables. In the present invention, however, the wall thickness of the piston is preferably made greater than the corresponding skin depth at the resonant frequency of the coil capacitor circuit. Therefore the piston, traveling through the coil, becomes a region from which the magnetic field of the coil is excluded.

If, for a short time, a conductor excludes a magnetic field, the field exerts a pressure upon the conductor. The value of this pressure is dynes/cm.<sup>2</sup> is

$$\frac{B^2}{8\pi}$$

where B is the magnetic field in gauss. This pressure is equivalent to the energy density in the magnetic field. Iron has the property of reducing this energy density and is therefore attracted into the magnetic field. Conversely a non-magnetic conductor, which excludes the field, is repulsed thereby. This repulsive force, equivalent to the magnetic pressure, results in the conductor being able to do work against the field by being forced into the field. Similarly if the conductor leaves the field, the field does work back upon the conductor.

The necessary condition for transferring energy from the piston to the resonant circuit is thus that the magnetic field be made high when the piston enters the coil and made lower before the piston leaves so that the piston does more work upon entering the field than the lower field does work back on the piston as it leaves.

The foregoing provides a mechanism for drawing electrical energy directly from a reciprocating piston engine without the use of complex rotary generators. It will further be found, where maximum compactness and simplicity is desired, that a novel form of engine is uniquely adapted to provide the reciprocating piston for delivering energy to the coil capacitor circuit. One form of such engine comprises a combustion cylinder formed of electrically resistive material, the piston being a free piston disposed within the cylinder for reciprocation therein. The coil of the coil capacitor circuit is disposed coaxially around the central portion of the cylinder, sufficient spacing between the ends of the coil and the ends of the cylinder being provided in order that the piston will travel completely through the coil in the course of reciprocation. To power the piston, fuel supply means such as diesel fuel injectors are provided at each end of the cylinder and air intake-exhaust ports are located centrally thereon. Provided the fuel supply means are timed to introduce a fuel charge into each end of the cylinder as the piston nears that end, the system will operate as a double ended free piston engine and extremely high power output is achieved.

The present invention serves to deliver an amount of electrical power far exceeding the output of conventional

systems of comparable size, and is characterized by extreme ruggedness, simplicity, and economy of cost, operation and maintenance.

It is therefore an object of this invention to provide improved apparatus for the generation of electrical energy.

It is a further object of this invention to provide a non-rotary electrical generation means characterized by simplicity and economy of operation.

It is an object of the invention to provide superior means for obtaining alternating electrical current directly from a driving engine without the intermediate use of generator apparatus of the class having moving parts.

It is an object of this invention to provide a generation system, free from moving parts, for converting the mechanical energy of a reciprocating piston into electrical energy.

Still another object of this invention is to provide an integral unitary mechanism functioning both as an electrical generator and driving engine therefor, which mechanism is characterized by minimum bulk and weight in relation to the power delivered.

It is an object of this invention to provide a free piston engine having non-moving components for converting the output of the engine to electrical energy.

Still a further object of this invention is to provide a double ended free piston internal combustion engine operating by the alternate combustion of fuel on each side of the piston and having novel means for initiating reciprocation of the piston and novel means for withdrawing energy from the piston in the form of alternating electrical current.

The invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood by reference to the following specification taken in conjunction with the accompanying drawing in which, -

Figure 1 is a simplified schematic view of certain of the electrical components of the invention,

Figure 2 is a general assembly view of a preferred embodiment of the invention,

Figure 3 is a longitudinal section view of portions of the apparatus shown in Figure 2,

Figure 4 is a cross-sectional view taken along line 4-4 of Figure 3 and further clarifying the structure of the apparatus shown therein, and

Figure 5 is a schematic circuit diagram of certain of the electrical components of the invention.

Referring now to the drawing, and more particularly to Figure 1 thereof, there will first be considered one of the unique features of the invention, specifically the mode of energy transfer between a moving conductor and a coil capacitor circuit resonant at an electrical frequency equivalent to the rate at which the conductor enters and leaves the field of the coil. In Figure 1 there is shown schematically a preferred arrangement of the conductor and resonant circuit in which the coupling between the two is maximized. A piston 11 is disposed as a free piston within a cylinder 12 which cylinder is formed of non-magnetic, and preferably non-conducting, material. A coil 13 is disposed coaxially around the central portion of the cylinder 12, the coil being sufficiently short in relation to the length of the cylinder that piston 11 may be driven completely through the coil and a substantial distance beyond each end thereof in the course of reciprocation. A capacitor 14 is electrically connected with coil 13 to form a resonant circuit therewith suitable values being chosen for each to establish resonance at the desired frequency.

It will be assumed for the purposes of the present discussion that piston 11 is being driven in cylinder 12 with a reciprocating motion having a mechanical frequency corresponding to the electrical frequency of the coil capacitor circuit. Suitable means for driving the piston 11

are an important feature of the invention and will hereinafter be described in detail.

Piston 11 is driven into the central region of coil 13 when the current to the coil from capacitor 14 is near maximum, thus at a time when the magnetic field of the coil is large. By the time the piston 11 moves away from the opposite end of the coil 13, the current has become lower so that less work is done upon the retreating piston by the field than the advancing piston did work upon the field. The net difference in kinetic energy of the piston 11 must appear as electrical energy in the coil capacitor circuit. The piston 11 reverses direction and is again driven into the coil 13 when the current therein has reversed and built up to a near maximum on the succeeding half cycle. A similar energy transfer takes place and both the piston 11 and resonant circuit have completed a cycle. The phase of the piston 11 reciprocation relative to the coil-capacitor current oscillation is maintained by what is characterized as non-linear coupling, which occurs when the magnetic field of the coil 13 is strong enough to appreciably slow down the piston. If, under such circumstances, the piston 11 is ahead in phase, that is it enters the coil 13 at the peak magnetic field therein, it is slowed and retarded in phase. Conversely if the piston 11 is behind in phase, entering the coil 13 at a moment of lower field, it is slowed much less and tends to advance in phase. Such coupling thus tends to lock in the reciprocation frequency of the piston 11 relative to the electrical frequency of the coil capacitor system.

A more mathematical treatment of the energy transfer can be made by observing that the piston 11 reciprocating in and out of the coil 13 represents an oscillating inductance, provided of course that at the frequency of oscillation the electrical skin depth in the piston is small compared with the diameter of the piston.

The voltage across the capacitor 14 becomes:

$$V = \frac{d}{dt}(LI)$$

where

$$\frac{d}{dt}$$

is the time derivative and both L (inductance) and I (current) are periodic functions of time. For the capacitor 14,

$$V = \frac{1}{C} \int Idt$$

where C is the capacitance, or

$$\frac{dV}{dt} = \frac{I}{C}$$

Differentiating the above and substituting one obtains:

$$\frac{I}{C} = \frac{d^2}{dt^2}(LI)$$

Letting  $X = LI$  the equation becomes:

$$\frac{d^2 X}{dt^2} - \frac{X}{LC} = 0$$

Since the parameter L is a periodic function of time, the above equation is of the Hill-Mathieu type which has the generalized solution by Floquet's theorem that:

$$X = a_1 e^{uP(t)} + a_2 e^{-uP(t)}$$

where  $a_1$  and  $a_2$  are constant coefficients and  $P(t)$  is a periodic function in time. The coefficient of the exponential is not determined but the positive exponent,  $a_1$  coefficient term, corresponds to the case of power generation in the coil capacitor circuit. For this solution X becomes a periodic exponentially increasing term. Since  $X = LI$ , and L is a bounded periodic function, then I, the current, is an unbounded periodic function. In practice the oscillations of the current increase in amplitude until

the dissipation factor into an external load, such as load 16 connected across capacitor 14, becomes equal to the power input and the amplitude of current oscillation then remains constant.

Considering now the effect of the load 16 on the system, it will be observed that in a conventional generator the effect of a resistive load is to reduce the frequency of the generator, slowing down the driving engine. Such reduction in frequency is customarily overcome by a speed governor on the driving engine. In the present invention, however, the frequency is fixed by the coil capacitor circuit so that a resistive load acts only to reduce the capacitor voltage and the coil current. In an extreme case where the coil current falls below a critical value, the coupling between the piston 11 and coil field will become low enough so that the two become out of phase and no power is generated, the action being somewhat equivalent to the stalling of a conventional motor by too sudden application of a load.

If the load 16 is reactive, the effect on the free piston generator is to slightly increase the resonant frequency of the coil capacitor circuit since a reactive load is equivalent to an inductance added in parallel to the inductance of coil 13. This added inductance is small since in general the power factor is not greatly different from unity. In addition the total load current is less than the coil current and therefore the frequency shift is smaller still since such frequency shift is proportional only to the square root of the change in total inductance. In the usual practice the power factor is corrected for by a condenser and such technique is fully applicable to the present invention.

The electrical efficiency of the cycle is determined by the resistive diffusion of the coil magnetic field into the piston 11. The distance of this diffusion, or skin depth, must be small compared to the radius of the piston for high electrical efficiency, the controlling relationship under such circumstances being:

$$\frac{\text{Piston volume—skin depth volume}}{\text{piston volume}}$$

Thus the skin depth must be less than one half the radius of the piston 11 if power is to be generated and for eighty percent efficiency the skin depth must be less than ten percent of the radius.

The physical size of the apparatus can vary between extremely wide limits. A minimum size is determined by the above discussed efficiency considerations since the ratio of the piston radius to the electrical skin depth of the piston material at the frequency of the coil capacitor circuit must exceed two to one if power generation is to be achieved. A piston diameter of one inch is representative of a minimum sized device but should not, however, be taken as an exact limiting size. Assuming a given form of engine driving the piston 11, the reciprocation frequency of the piston decreases in inverse proportion to an increase in the size of the apparatus. The electrical skin depth, however, becomes larger only in proportion to the square root of such increase. It follows then that the electrical efficiency of the apparatus increases in proportion to its size and therefore large installations utilizing pistons several feet in diameter are entirely feasible. The one limitation on extremely large size, in installations where internal combustion engine means are used to directly drive the piston, is the difficulty of cooling because the piston surface area does not increase with size in proportion to the increase in heat output.

Since, as explained above, the efficiency of the generator increases with a decrease of the coil field penetration into the piston 11, and such penetration is less the higher the frequency of the field, it follows that the piston should be driven extremely rapidly in order to be in phase with the maximum possible electrical frequency. In order to meet the requirements of maximum piston reciprocation frequency with minimum bulk, weight, and complexity, the present invention includes a novel free

piston engine which forms a unitary device with the components heretofore described. It will be understood, however, that the piston 11 may be driven through the coil 13 by a variety of other means, examples of which will hereinafter be pointed out.

Referring now to Figure 2 for a general assembly view of a representative embodiment of the invention, and to Figures 3 and 4, for the details of certain of the components thereof, it may be seen that the cylinder 12 is formed as a combustion cylinder since internal combustion means are used to drive the apparatus. As best shown in Figure 3, cylinder 12 is provided with a flange 17 at each end to which circular head plates 18 are secured by studs 19, suitable gaskets 21 being disposed between the members. The cylinder 12 is formed of material having high electrical resistance so that the magnetic field can penetrate without inducing large eddy current losses, silicon resin and glass cloth composition or stainless steel being suitable materials. The central portion of cylinder 12 is preferably provided with longitudinal slots 22 alternated with longitudinal ribs 23 which ribs facilitate cooling of the cylinder and increase the circumferential resistance thereof. Four intake-exhaust openings 24 are spaced ninety degrees apart at the center of the cylinder, the openings being elongated in a direction parallel to the axis of the cylinder.

Free piston 11, having a diameter conforming to the internal diameter of cylinder 12, is disposed coaxially within the cylinder for reciprocation therein, the piston preferably having a length less than one-third the axial length of the cylinder. Where, as in the present embodiment, fast reciprocation of the piston 11 is desired, the piston should be hollow and should be formed of lightweight conducting material such as aluminum. As has hereinbefore been pointed out, the thickness of the walls 26 of the piston 11, should be at least equal to the electrical skin depth of the piston material at the frequency of the current which is to be generated. By way of illustration, the present embodiment utilizes a four inch diameter aluminum piston reciprocating at sixty cycles per second and the thickness of walls 26 is therefore one-fourth inch. The present embodiment of the invention utilizes no piston rings inasmuch as the extreme speed of the piston 11 reduces blow-by to a negligible value.

To supply combustible fuel to each end of cylinder 12, a diesel fuel injector 27 is secured in coaxial relationship to each head plate 19, the injectors projecting axially from cylinder 12 and the spray nozzles 28 of each such injector being directed into a central aperture 29 in each head plate. The injectors 27 are of the class which inject a fuel charge in response to an elevation of pressure within the cylinder, which pressure elevation is produced by the approach of piston 11 towards an end of the cylinder and which pressure elevation is sensed by the spray nozzle 28. Suitable fuel injectors of this class are disclosed in detail in my copending application Serial No. 623,034, filed November 19, 1956 and entitled, Internal Combustion Apparatus.

As shown in Figure 2, the fuel inlets 31 to the injectors 27 are connected with a pressurized fuel bottle 32 by means of tubulations 33, any of the customary diesel fuels being suitable for use with the invention.

The above described elements of the invention constitute a double ended free piston internal combustion engine. As the piston 11 approaches a given end of cylinder 12, air in the cylinder is compressed which pressure reacts against fuel injector spray nozzle 28 causing a charge of fuel to be injected into the cylinder. Combustion of the fuel charge, initiated by the adiabatic heating accompanying compression of the air within the cylinder 12, further elevates the pressure within the cylinder and drives the piston 11 towards the opposite end thereof. As the piston 11 passes intake-exhaust

openings 24 the high pressure combustion products within the cylinder are expelled. Motion of the piston on past the openings 24 serves to draw a fresh charge of air into the cylinder which air charge serves to support combustion of the fuel during the subsequent cycle. Such motion of the piston 11 further serves to produce a fuel charge combustion at the opposite end of the cylinder 12 returning the piston towards the first end of the cylinder. In this manner, the piston 11 continually reciprocates within the cylinder 12 producing a very high degree of power, which energy is withdrawn from the piston by electrical means to be hereinafter described.

As is apparent from the foregoing, a starting means must be provided to initiate reciprocation of the piston 11, within the cylinder 12 since the injection and ignition of a fuel charge is dependent upon the piston being very forcibly driven towards one end of the cylinder. Such starting means, in this embodiment, comprises a compressed air tank 34 and a valve assembly 36 for directing air from the tank alternately to the two ends of combustion cylinder 12 thereby causing reciprocation of the piston within the cylinder, which reciprocation builds up to the point where ignition of a fuel charge takes place. The tank 34 may, if desired, be situated remotely from the remainder of the apparatus, the tank being provided with an outlet valve 37 which connects with the valve assembly 36.

Referring now to Figure 3 in particular, for the detailed structure of valve assembly 36, it should be observed that the extreme speed with which the main piston 11 oscillates within the combustion cylinder 12 virtually rules out a valve system which operates by direct mechanical coupling with the piston. The valve, in this embodiment, constitutes a second smaller free piston reciprocating in a second cylinder, pressure feedback means being provided to establish resonance between the two pistons. The second cylinder comprises a secondary cylinder 39 having an axial bore 41 which bore is enlarged at each extremity to form internally threaded cylinder head receiving chambers 42. Cylindrical head members 43 project coaxially into chambers 42 and are provided with a projection 44 of lesser diameter which extends a short distance into the bore 41. Head members 43 are threaded to engage the internal threads in chambers 42 so that rotation of the head members will advance or retract projections 44 in the cylinder 39, thereby effectively lengthening or shortening the bore 41, for purposes which will hereinafter be discussed. To facilitate such adjustment of the head members 43 the ends thereof which project from the cylinder are provided with hexagonal heads 46 for easy gripping thereof with a wrench.

To lock the head members 43 in a desired position once a suitable adjustment has been made, lock nuts 47 are disposed coaxially on the head members and are threadably engaged therewith, the lock nuts bearing against the ends of the secondary cylinder 39. The outer surface of the secondary cylinder 39 is provided with three coaxial annular grooves, one such groove 48 being situated centrally on the cylinder and the other two grooves being situated one on either side of the central groove and being spaced substantially half way between the center of the cylinder and the valve head members 43. The central groove 48, which serves as the compressed air inlet, is communicated with the interior of the cylinder 39 by four air inlet apertures 51 in the cylinder wall which apertures are spaced ninety degrees apart. Similarly the side grooves 49, which connect the secondary cylinder with the combustion cylinder 12, each communicate with the interior of the cylinder by means of four quadrantly spaced apertures 52. To enclose the air passages formed by the grooves 48 and 49 and associated apertures 51 and 52, a cylindrical cover 53 is secured coaxially around secondary cylinder 39 in close fitting relationship.

Each of the side grooves 49 of the secondary cylinder 39 is communicated with one of two ports 54 which ports transpierce the wall of combustion cylinder 12, suitably angled tubulations 56 being utilized to make the connection. The longitudinal position of ports 54 on the combustion cylinder 12 is determined by the requirement that when the main piston 11 has compressed trapped air adiabatically up to a pressure equal to that of the compressed air used for starting the engine, the piston should just close the port. By way of example, the present embodiment utilizes starting air compressed to 100 pounds per square inch and the ports 54 are therefore situated at points three fourths of the distance from intake-exhaust openings 24 to head plates 18. The connecting tubulations 56 are formed with a first section 57 projecting radially from an opening 58 in secondary cylinder cover 53, the opening being communicated with groove 49. The intermediate section 59 of each tubulation 56 is aligned parallel with the secondary cylinder 39 and terminates in an enlarged valve housing 61. The third section 62 of each tubulation 56 projects from valve housing 61 at right angles to intermediate section 59 and terminates at a flange 63 which flange is secured to the wall of the combustion cylinder 12 over port 54. It will be understood that the foregoing configuration of the tubulations 56 arises from the parallel alignment of the combustion cylinder 12 and the valve assembly 36 in this embodiment. Such alignment is not critical however and the tubulations 56 might take different forms to accommodate different placements of the cylinders.

To provide a means for isolating the valve assembly 36 from the combustion cylinder 12 once self sustained operation of the free piston engine has commenced, a valve 64 is provided in each tubulation 56. Each such valve comprises a threaded valve stem 66 engaging a threaded bore 67 in valve housing 61, the bore being opposite the termination of intermediate tubulation section 59 and being aligned coaxially therewith. A circular valve disc 68 is secured coaxially to the end of stem 66 within the valve housing 61 and a circular handle 69 is secured coaxially to the opposite end of the stem to facilitate rotation thereof. Thus rotation of handle 69 advances or retracts disc 68 from the extremity of intermediate tubulation section 59 and the tubulation 56 may be opened or closed as needed.

Compressed air is alternately directed to each end of combustion cylinder 12 largely through the action of a second free piston 71 which piston is disposed coaxially within bore 41 of secondary cylinder 39 for reciprocation therein, the piston again being of hollow construction to minimize weight.

To provide a means for positioning the pistons 11 and 71 in the proper relationship for starting the engine, the conduit 38, supplying compressed air, connects with the valve assembly 36 through an eductor assembly 72. The eductor 72 comprises a stepped cylinder 73 projecting radially from a central position on secondary cylinder cover 53, the interior of cylinder 73 being communicated with inlet groove 48 in secondary cylinder 39 by means of an opening 74 in the cylinder cover. Eductor cylinder 73 is positioned with the section 76 of greatest diameter furthest from the secondary cylinder and the extremity of the cylinder section is externally threaded to engage the inlet side of a gate valve 77. Valve 77 is of standard construction comprising a cylindrical case 70, having a radially projecting gate housing 75 and a threaded valve stem 80 transpierced through a threaded aperture in the end of the gate housing. A handle 85 is secured coaxially to the outer end of the valve stem 80 and the inner end of the stem is pivotally connected with the periphery of a circular valve gate 90, rotation of the valve stem thus acting to withdraw the gate from a transverse position in case 70 into the gate housing 75 thereby opening the valve.

Conduit 38 from the compressed air supply is trans-

pierced through the wall of eductor cylinder section 76 and the extremity 78 of the conduit is angled to be directed towards valve 77. Conduit extremity 78 is terminated a small distance short of valve 77 to provide an air passage through the eductor cylinder to secondary cylinder 39 and to produce the required eductor action. Thus with valve 77 closed, compressed air is delivered to the secondary cylinder 39. When the valve 77 is opened, however, a reverse air flow is obtained since the jet of air emerging from conduit extremity 78 is expelled to the atmosphere and in the process entrains air in the eductor cylinder 73 producing a suction through opening 74 leading to the secondary cylinder 39.

Accordingly, the pistons are positioned for starting by opening gate valve 77 and momentarily turning on the compressed air. The resultant suction through the secondary cylinder 39, tubulations 56, and combustion cylinder 12 causes the main piston 11 to be drawn towards one extremity of the combustion cylinder. Concurrently the air flow towards the center of secondary cylinder 39 draws the secondary piston to a central position therein. When the pistons have been positioned in this manner, the compressed air is turned off and the valve 77 closed.

Following the above procedure, reciprocation of the pistons is initiated by again turning on the compressed air. Considering now the manner in which such reciprocation is induced, it may be seen that with the pistons positioned as indicated above, air entering the secondary cylinder 39 through inlet ports 51 will flow primarily towards only one end of the secondary cylinder since the outlet at the opposite end of the cylinder, through tubulation 56 and combustion cylinder 12, is blocked by the main piston 11. Such air flow, between the secondary piston 71 and the adjacent cylinder wall, will carry the secondary piston towards the unblocked tubulation 56 or away from main piston 11. Once the secondary piston 71 leaves the central position, thus fully opening the inlet ports 51, the full air pressure is applied to the main piston 11 which is driven forcibly to the opposite end of combustion cylinder 11.

As the main piston 11 is driven to one end of the combustion cylinder 12, air is forced through the tubulation 56 at that end of the cylinder into the secondary cylinder 39 which air in turn drives the secondary piston 71 in the opposite direction. Such motion of the secondary piston past the mid-point of the secondary cylinder switches the compressed air to the opposite face of the main piston 11 returning the main piston to its original position, whereupon a subsequent cycle of reciprocation is brought about in a similar manner.

With each cycle of reciprocation of the pistons, the amplitude of oscillation increases, the increased energy being derived from the compressed air supply. When the energy of the main piston 11 reaches a certain value, the head pressure created at the ends of the combustion cylinder 12, by motion of the piston, will be sufficient to trigger fuel injectors 27 and to initiate combustion of the fuel charge. At this point operation of the engine as an internal combustion device commences and the compressed air supply can be shut off and the valves 64 closed to isolate the secondary cylinder 39 from the combustion cylinder 12.

It will be observed that the secondary piston 71 is kept in phase with the main piston 11 by pressure coupling through the tubulations 56. Such coupling has the property that when the secondary piston 71 is ahead in phase from the proper relationship, energy is fed from the secondary piston to the main piston 11 thus slowing the secondary piston and restoring the proper phase relationship. Conversely when the secondary piston 71 is behind in phase, energy is fed thereto by the main piston 11. The phase coupling is critical to the operation of the valve assembly 36 and may best be understood by assuming the

compressed air inlet ports 51 to be momentarily closed as the pistons are in the process of reciprocating. Under this condition the secondary piston 71 will try to oscillate 180° out of phase with the main piston 11. With the inlet ports 51 open, which is the actual operating condition, the secondary piston 71 is retarded in phase with respect to the main piston 11 since the effect of compressed air from the inlet ports is always to increase the pressure ahead of the secondary piston. In the absence of this phase lag, the energy gained by the main piston 11 from the compressed air in the first half of a stroke would be just cancelled by the energy lost by the piston in pushing against the compressed air in the second half of the stroke. Thus no net energy would have been gained by the piston at the completion of a cycle. The effect of the phase lag, however, is to cause the compressed air to drive the piston 11 for a longer proportion of the stroke than the proportion of the stroke in which it works against the piston, the result being a net energy gain by the piston. Thus the energy of the piston continually builds up, producing higher and higher head pressures at the ends of the cylinder 12, until combustion of a fuel charge is finally initiated.

The magnitude of this phase lag is determined, in part, by the length of the bore 41 in which the secondary piston 71 reciprocates. Thus the phase lag may be adjusted to an optimum value by advancing or retracting the head members 43 thereby effectively lengthening or shortening bore 41. In theory the best value for the phase lag could be calculated and the bore 41 fixed at a definite length. Such calculation is, however, an extremely complicated treatment of coupled resonant systems and the calculated value may become unsuitable if some small change in operating conditions occurs. It is therefore more convenient to arrive at the proper value empirically by trial adjustment of the head members 43.

Considering now the means by which energy is withdrawn from the main piston 11 and converted to electrical energy, coil 13 is mounted coaxially around the central portion of the combustion cylinder 12. The coil 13 must have an internal diameter somewhat greater than the external diameter of combustion cylinder 12 to avoid impeding gas flow through cylinder intake-exhaust ports 24, and is preferably wound of conductor having a square cross section and an internal coolant passage 79. The electrical characteristics of the coil 13 will be hereinafter discussed, it should be pointed out however that the coil preferably has an axial length considerably smaller than the length of the combustion cylinder 12 in order that the main piston 11 will clear the interior of the coil by a substantial distance in the course of reciprocation, the extent of such clearance being as high as is mechanically feasible. As best shown in Figure 2, the coil 13 is held in place by four pairs of brackets 81 spaced ninety degrees apart around the circumference of the combustion cylinder 12, each such bracket having a base portion 82 secured to the cylinder by means of bolts 83, a central portion 84 extending radially from the cylinder in the plane defined by the end of the coil, and a top portion 86 at right angles to the central portion and extending a short distance over the outer surface of the coil.

To shield the coil 13 from the hot exhaust gases expelled through openings 24, four thin arcuate baffles 87 of V-shaped cross section are disposed between cylinder 12 and the coil, the apex of the baffles being secured to the central circumference of the cylinder 12 by means of fasteners 88, the arms of the baffles extending outward from the cylinder and towards the ends thereof. One of the baffles 87 is centered on each of the four intake exhaust ports 24. The two terminals 89 of coil 13 are provided with fittings 91 each of which connects with a coolant conduit 92 formed of non-conducting material, such conduits being in turn connected with a suitable source of cooling water which then circulates through the internal passages 79 of the coil conductor. The termi-

nals 89 are connected by means of a double conductor cable 93 with a second pair of terminals 94 on a remotely situated capacitor housing 96. It will be understood that cable 93 should be formed of very thick conductors to avoid heating damage from the high currents present in the coil-capacitor circuit.

Referring now to Figure 4, the electrical components within the capacitor housing 96 are shown schematically to facilitate description thereof, such components, taken individually, being conventional items familiar to those skilled in the art. Capacitors 14 are connected in parallel to terminals 94, the number of such capacitors being a matter of convenience except insofar as the total capacity must, in conjunction with the inductance of the associated coil 13, form a circuit resonant at the frequency of alternating current which is to be generated. It will be apparent to those skilled in the art that the capacitors 14 may be replaced with other suitable energy storage means. In large installations, for example, the capacitors 14 might conveniently be replaced with synchronous motors. Also disposed within capacitor housing 96 is a voltage overload control comprising a normally open relay 98, the winding 99 of which is connected in parallel with capacitors 14. One contact 101 of the relay connects with a first side of the capacitors 14 and the second contact 102 of the relay connects through a load resistor 103 with the opposite side of the capacitors. Thus when the voltage across the capacitors 14 reaches a maximum value, relay 98 closes placing the resistor 103 in parallel with the capacitors and reducing the voltage thereacross.

Current is withdrawn from the coil capacitor circuit by connecting the load with capacitor housing terminals 94. Where it is desired, the terminals 94 may be connected with an existing power distribution system. The electrical characteristics of the coil 13, capacitors 14, and other electrical components, are determined by the frequency and amplitude of current to be generated and by the power output of the piston driving means. In the present illustrative embodiment which uses a four inch diameter piston reciprocating at sixty cycles per second and driven with a mean effective diesel cycle pressure of fifty pounds per square inch and in which 440 volt power is developed, the capacitors 14 have a total capacity of 1400 microfarads. The coil 13 has 225 turns with a thickness of one-half inch, a length of three inches, and an inner diameter of five inches. The energy stored in the capacitors 14 at peak voltage is 275 joules and the peak coil magnetic field is 5000 gauss. The output of the piston driving means is approximately sixty horsepower. In calculating suitable parameters for installations of other sizes, it must be borne in mind that the maximum coil magnetic field pressure on the piston should be somewhat greater than the mean effective driving pressure on the piston from combustion gases if good coupling between the piston and the magnetic field is to be achieved.

If too heavy a load is coupled to the coil capacitor circuit, the coil current may be reduced to the point where coupling between the coil magnetic field and the piston fails. It may therefore be found advisable, in systems where widely varying loads may be applied to the generator, to provide a fuel governor controlled by the voltage across the capacitors 14, which mechanism increases the fuel charge supplied the combustion cylinder 12 by injectors 27 in response to a decrease in capacitor voltage.

Considering now the operation of the electrical features of the invention, with reference to Figures 2, 3, and 5, in particular, it will be assumed that the main piston 11 is being driven reciprocally within combustion cylinder 12 by the engine mechanism hereinbefore described. Some slight eddy currents will be induced in the piston 11 by interaction with any stray magnetic field present, for example by interaction with the Earth's magnetic field. Such eddy currents will in turn give rise to mag-

netic fields which induce a small current in the coil 13. Since the coil 13, in conjunction with the associated capacitors 14, is a resonant circuit, the induced currents produce oscillation at the resonant frequency. When the period of reciprocation of the piston 11 reaches a value equivalent to the resonant frequency of the circuit, a strong coupling between the piston and the magnetic field of the coil exists, the mechanism of which has been previously described. Once such coupling is brought about, the amplitude of current within the coil capacitor circuit rapidly builds up to very high values, the amplitude being ultimately limited by the resistance of the coil capacitor circuit together with the resistance of the load which is coupled into the circuit.

Owing to the light weight piston and the extremely high cycle rate, as well as the other novel aspects of the apparatus, the power generated by the invention is five to ten times greater than that produced by a conventional engine-generator installation of comparable bulk.

The present invention, in common with most prior forms of electrical generator, will function as an electrical motor where current is supplied to what would ordinarily be the output terminals. To achieve such operation the fuel injectors 27 must be rendered inoperative, or removed, and reciprocation of the main piston 11 at a rate corresponding to the resonant frequency of the coil-capacitor circuit must be initiated by the compressed air starting system. If current alternating at the resonant frequency of the coil capacitor circuit is applied to terminals 94, coupling between the magnetic field of the coil 13 and the piston 11 occurs in a manner analogous to that occurring in the case of power generation. The compressed air may then be shut off and reciprocation of the piston will be continued by interaction of the piston with the coil magnetic field. An example of a use of the invention as a motor is use as an air compressor which is accomplished by connecting conduits from compressed air storage vessel into the central apertures 29 in cylinder head plates 18, the fuel injectors 27 having been removed. If check valves are provided in the conduits so that air can flow only away from the cylinder, each reciprocation of the piston will force air into the storage vessel.

Other modes of operation of the invention are possible. For example the fuel injectors 27 may be removed and the injector ports 29 sealed, the generator then being operated solely by compressed air from supply vessel 34. Similarly the compressed air supply vessel 34 may be replaced with a source of high pressure steam, such as a boiler, and operated therefrom, the apparatus thus constituting a steam generation plant. Variations of the invention are possible wherein fuel is injected at only one end of the cylinder 12, the piston being returned by such means as a spring or an air cushion.

Thus while the invention has been disclosed with respect to a single embodiment, it will be apparent that those skilled in the art that numerous variations and modifications may be made within the spirit and scope of the invention and thus it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. In an electrical generator, the combination comprising a coil element, an energy storage device connected with said coil element to establish a resonant circuit in conjunction therewith, a piston member formed of non-magnetic electrically conducting material, said piston member being disposed in the vicinity of said coil element, and engine means reciprocating said piston member whereby said piston member interacts with the magnetic field of said coil element and energy generated by said engine means is transferred to said resonant circuit.

2. In an electrical generator the combination comprising a coil element, an energy storage means connected with said coil element and establishing an electrically resonant circuit therewith, a piston element formed of

13

electrically conductive non-magnetic material, said piston element being disposed in the vicinity of said coil element, and motor means reciprocating said piston element in a direction paralleling the axis of said coil element whereby said piston interacts with the magnetic field of said coil element and transfers energy to said resonant circuit.

3. An electrical generator comprising, in combination, an electrical coil, an energy storage means connected with said coil and forming an electrically resonant circuit therewith, a piston member formed of conducting non-magnetic material, said piston member being positioned for reciprocation in the magnetic field of said coil, and engine means imparting a reciprocating motion to said piston member whereby mechanical energy of said piston member appears as electrical energy in said electrically resonant circuit.

4. An electrical generator comprising, in combination, a solenoidal coil, an electrical energy storage means connected with said coil and establishing a resonant circuit therewith, an electrically conducting non-magnetic piston mounted to reciprocate along the axis of said solenoidal coil, and engine means producing reciprocatory motion of said piston along said axis of said coil whereby said piston interacts with the magnetic field of said coil transferring energy thereto.

5. An electrical generator comprising, in combination, a hollow cylinder, a piston element disposed within said cylinder for reciprocation therein, said piston element being formed of electrically conducting non-magnetic material, an electrical coil disposed coaxially around the central portion of said cylinder, at least one capacitor connected with said coil and forming an electrically resonant circuit therewith, and engine means reciprocating said piston within said cylinder whereby the mechanical energy of said piston is converted to electrical energy in said resonant circuit.

6. Means for the generation of electrical energy comprising, in combination, a cylinder having high circumferential electrical resistance, a non-magnetic electrically conductive piston disposed within said cylinder for reciprocation therein, drive means reciprocating said piston within said cylinder, a solenoidal coil disposed coaxially about the central portion of said cylinder, and an electrical energy storage device connected with said solenoidal coil and forming a resonant circuit in conjunction therewith whereby kinetic energy of said piston is converted to electrical energy within said resonant circuit.

7. Apparatus for the generation of electrical power comprising, in combination, a hollow cylinder, an electrically conducting non-magnetic piston disposed in said cylinder for reciprocation therein, said piston substantially corresponding in diameter to the internal diameter of said cylinder whereby a high pressure region is created at a first end of said cylinder by movement of said piston therein, means supplying combustible fuel to said high pressure region at said first end of said cylinder, the combustion of said fuel driving said piston away from said first end of said cylinder, means forcibly returning said piston towards said first end of said cylinder for initiation of a subsequent cycle, a solenoidal coil disposed coaxially around said cylinder and spaced a substantial distance from said first end thereof, and a capacitor connected across said coil and forming a resonant circuit therewith whereby the mechanical energy of said piston is converted to electrical energy in said resonant circuit by interaction of said piston with the magnetic field of said coil.

8. In an electrical generator, the combination comprising a combustion cylinder, an electrically conducting non-magnetic piston disposed in said cylinder for reciprocation therein, fuel supply means periodically introducing combustible fuel into a first end of said cylinder, combustion of said fuel producing a power stroke of said piston and driving said piston away from said first end of

14

said cylinder, means for venting said first end of said cylinder of combustion products and for introducing a fresh charge of air into said first end of said cylinder, means returning said piston towards said first end of said cylinder for compression of said air charge, an electrical winding disposed coaxially around said combustion cylinder, said winding being spaced a substantial distance from said first end of said cylinder, and an electrical capacitor connected with said winding and forming a resonant circuit therewith.

9. An electrical generator substantially as described in claim 8 wherein said electrical winding is spaced from said first end of said cylinder a distance exceeding the length of said piston.

10. An electrical generator comprising, in combination with an internal combustion engine of the class having a combustion cylinder and an electrically conducting non-magnetic piston driven reciprocally therein, a solenoidal coil disposed coaxially around said combustion cylinder, at least one capacitor connected with said coil and forming an electrically resonant circuit therewith, and terminals disposed in said resonant circuit for withdrawing alternating electrical current therefrom, said current being induced in said circuit by reciprocation of said piston through the magnetic field of said coil.

11. An electrical generator comprising, in combination, an internal combustion engine having a combustion cylinder with a high circumferential electrical resistance and an electrically conductive non-magnetic piston driven reciprocally within said cylinder, an electrical coil disposed coaxially around said combustion cylinder of said internal combustion engine, said electrical coil being spaced from at least one end of said combustion cylinder a distance exceeding the length of said piston, and an electrical capacitor connected with said coil and forming a resonant circuit therewith whereby said reciprocating piston induces an alternating current within said circuit by periodical compression of the magnetic field of said coil.

12. Apparatus for the generation of electrical energy comprising, in combination, a combustion cylinder having high circumferential electrical resistance, said combustion cylinder being characterized by at least one intake-exhaust vent at a central position thereon, a cylindrical electrically conducting piston of non-magnetic material disposed in said cylinder for reciprocation therein, said piston conforming in diameter to the internal diameter of said cylinder whereby reciprocation of said piston compresses air alternately at each end of said cylinder, fuel injector means supplying combustible fuel to each end of said cylinder as said air is compressed therein whereby said reciprocating motion of said piston is produced, an electrical coil disposed coaxially around the central portion of said cylinder, and a capacitor connected with said coil and forming a resonant circuit in conjunction therewith.

13. In apparatus for the generation of electrical energy substantially as described in claim 12, the further combination of means for starting reciprocation of said piston comprising a secondary cylinder having each end communicated with an end of said combustion cylinder, a secondary free piston disposed in said secondary cylinder for reciprocation therein, and a source of compressed gas communicating with the central portion of said secondary cylinder whereby said compressed gas causes said piston to reciprocate within said combustion cylinder and said secondary piston to reciprocate within said secondary cylinder, said secondary piston acting to switch said compressed air alternately to each end of said combustion cylinder.

14. In an electrical generator for producing alternating current at a selected frequency, the combination comprising a combustion cylinder having high circumferential electrical resistance and having at least one intake-exhaust port located substantially midway between the ends

thereof, a cylindrical piston formed of electrically conducting non-magnetic material disposed coaxially within said combustion cylinder for reciprocation therein, said piston having a hollow construction with a wall thickness at least as great as the electrical skin depth of said material for a field of said selected frequency, said piston acting to compress air alternately at each end of said combustion cylinder, fuel injector means introducing combustible fuel alternately into each end of said combustion cylinder whereby reciprocation of said piston is maintained, a solenoidal coil disposed coaxially around the central portion of said combustion cylinder, and an electrical circuit connected with said coil, said circuit including suitable capacitance for establishing resonance at said selected frequency.

15. Electrical generator apparatus comprising, in combination, a first cylinder having an intake-exhaust port situated centrally thereon, said cylinder being formed to have high circumferential electrical resistance, a first hollow piston disposed within said first cylinder for reciprocation therein, said first piston being formed of electrically conducting non-magnetic material and having a length substantially less than one half the length of said first cylinder, injector means supplying fuel alternately to each end of said first cylinder whereby combustion of said fuel drives said first piston reciprocally within said cylinder, an electrical coil disposed coaxially around the central portion of said first cylinder, said coil being distant from the ends of said first cylinder a distance exceeding the length of said first piston, a capacitor connected with said coil and forming a resonant circuit therewith whereby the energy of said first piston is transferred to said resonant circuit by interaction of said first piston with the magnetic field of said coil, a second cylinder, a pair of valved tubulations one connecting each end of said second cylinder with an end of said first cylinder, a second piston disposed within said second cylinder for reciprocation therein, and a source of compressed gas communicating with the central region of said second cylinder whereby said compressed gas drives said first and second pistons within said first and second cylinders respectively to initiate operation of said generator, said second piston acting to direct the force of said compressed gas against alternate ends of said first piston.

16. An electrical generator substantially as described in claim 15 wherein said second cylinder is provided with adjustable head means for selectively varying the length thereof whereby the phase relationship between said first and second pistons may be adjusted.

17. In an electrical generator the combination comprising a combustion cylinder having an intake-exhaust port situated at the central section thereof and having a starting air port proximal to each end thereof, a hollow electrically conducting non-magnetic free piston disposed in said combustion cylinder for reciprocation therein, a pair of fuel injectors one mounted at each end of said combustion cylinder, said fuel injectors being of the class injecting fuel into said combustion cylinder upon a pressure rise therein which pressure rise is produced by approach of said piston towards an end of said combustion cylinder, an electrical coil positioned coaxially around the central section of said combustion cylinder, at least one capacitor connected with said coil and forming a resonant circuit therewith whereby the energy of said piston is transferred to said resonant circuit by interaction of said piston with the magnetic field of said coil, a secondary cylinder smaller than said combustion cylinder, each end of said secondary cylinder having a port communicating with one of said pair of starting air ports on said combustion cylinder, said secondary cylinder further having a central inlet port for the admission of compressed gas, a compressed gas source connected with said inlet port of said secondary cylinder, a secondary free piston disposed within said secondary cylinder for reciprocation therein whereby said compressed gas is

alternately directed to each end of said combustion cylinder for initiating reciprocation of said piston therein, and valve means closing said starting air ports on said combustion cylinder upon the initiation of combustion of said fuel.

18. In a free piston internal combustion engine, the combination comprising a combustion cylinder having an intake-exhaust opening located midway thereon, a free piston disposed within said combustion cylinder for reciprocation therein, a pair of diesel fuel injectors one disposed at each end of said combustion cylinder in position to inject fuel charges thereinto, said fuel injectors being of the class which inject fuel upon a pressure rise within said cylinder whereby said fuel injectors supply fuel alternately to each end of said combustion cylinder to maintain reciprocation of said piston in said combustion cylinder and means for initiating reciprocation of said piston in said combustion cylinder.

19. A free piston internal combustion engine substantially as described in claim 18 wherein said means for initiating reciprocation of said piston comprises a secondary cylinder each end of which is communicated with a corresponding end of said combustion cylinder through a valved tubulation, a secondary free piston slidably disposed in said secondary cylinder for reciprocation therein, and a compressed gas source connected with a central portion of said secondary cylinder whereby said first piston and said secondary piston are caused to reciprocate within their respective cylinders, said secondary piston acting to alternate the force of said compressed gas against the two ends of said first piston.

20. Means for converting electrical energy to mechanical energy comprising, in combination, a cylinder having high circumferential electrical resistance, an electrically conducting non-magnetic piston disposed in said cylinder for reciprocation therein, a coil disposed coaxially around the central portion of said cylinder, an electrical capacitor connected with said coil and forming a resonant circuit therewith, means initiating reciprocation of said piston within said cylinder, and means supplying alternating electrical current to said resonant circuit at the resonant frequency thereof whereby said current induces an alternating magnetic field around said coil maintaining reciprocation of said piston within said cylinder.

21. An electrical motor operating from alternating current of a selected frequency comprising, in combination, a cylinder having high circumferential electrical resistance, a hollow piston formed of conducting non-magnetic material slidably disposed in said cylinder for reciprocation therein, said piston having a wall thickness at least equal to the electrical skin depth of said material for a magnetic field oscillating at said selected frequency, an electrical coil wound coaxially around the central portion of said cylinder each end of said coil being spaced from the ends of said cylinder a distance exceeding the length of said piston, an electrical capacitor connected with said coil and having a capacity which forms a resonant circuit with said coil at said selected frequency, means supplying electrical current of said selected frequency to said resonant circuit, and mechanical means for initiating reciprocation of said piston.

22. A gas pressure driven engine comprising, in combination, a first cylinder having a central outlet opening and having at least a pair of gas inlet ports spaced one on either side of said central outlet opening, a first free piston disposed coaxially within said first cylinder for reciprocation therein, a secondary cylinder having a smaller volume than said first cylinder and having a central compressed gas inlet port and having at least a pair of gas outlet ports spaced one on either side of said central inlet port, tubulation means connecting each one of said gas outlet ports of said secondary cylinder with one of said gas inlet ports of said first cylinder, a secondary free piston disposed coaxially in said secondary cylinder for reciprocation therein, and a source of compressed driving gas

## 17

connected with said central inlet port of said secondary cylinder whereby said first free piston and said secondary free piston are caused to reciprocate in said first cylinder and said secondary cylinder respectively, said secondary piston acting to alternate the force of said compressed gas against the two sides of said first piston imparting energy thereto.

23. A gas pressure driven engine substantially as described in claim 22 wherein said secondary cylinder is provided with mechanism for adjusting the internal axial length thereof whereby the phase relationship between said first piston and said secondary piston may be controlled.

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