

(54) **FUEL INJECTION DRIVER CIRCUIT WITH ENERGY STORAGE APPARATUS**

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(58) **Field of Search** 417/53, 415, 417, 417/45, 63, 410.1, 360; 123/516, 490, 478, 480, 179.15, 179.21, 494, 486, 689, 198

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(57) **ABSTRACT**

A reciprocating pump includes a drive section and a pump section. The drive section has a reciprocating coil assembly to which alternating polarity control signals are applied by a reciprocating circuit during operation. A permanent magnet structure of the drive section creates a magnetic flux field which interacts with an electromagnetic field produced during application of the control signals to the coil. Depending upon the polarity of the control signals applied to the coil, the coil is driven in one of two directions of movement. The reciprocating circuit employs a storage capacitor and several switches to capture the energy of the reciprocating coil as the pump is driven downwardly. The charge is recycled as the capacitor dissipates, thereby reversing the polarity of the current through the coil and driving the coil assembly upwardly to its initial position. A drive member transfers movement of the coil to a pump element which reciprocates with the coil to draw fluid into a pump chamber and expel the fluid during each pump cycle. The pump is particularly well suited to cyclic pumping applications, such as fuel injection systems for internal combustion engines.

55 Claims, 5 Drawing Sheets

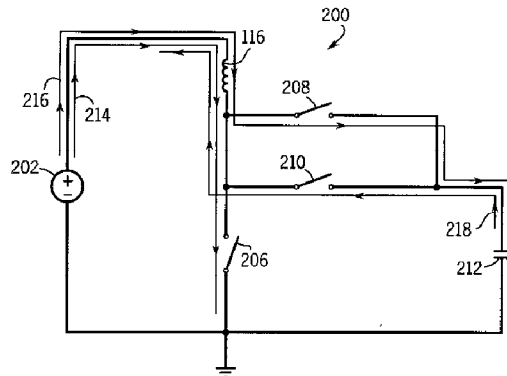
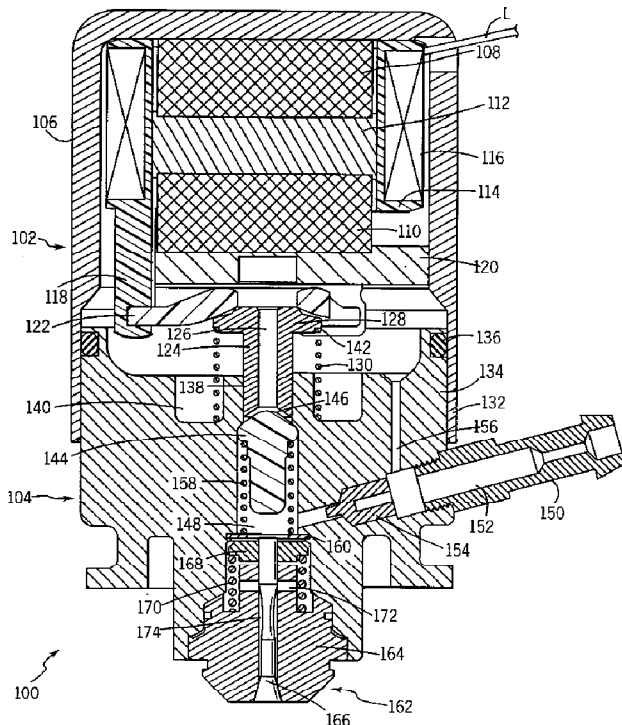


FIG. 1

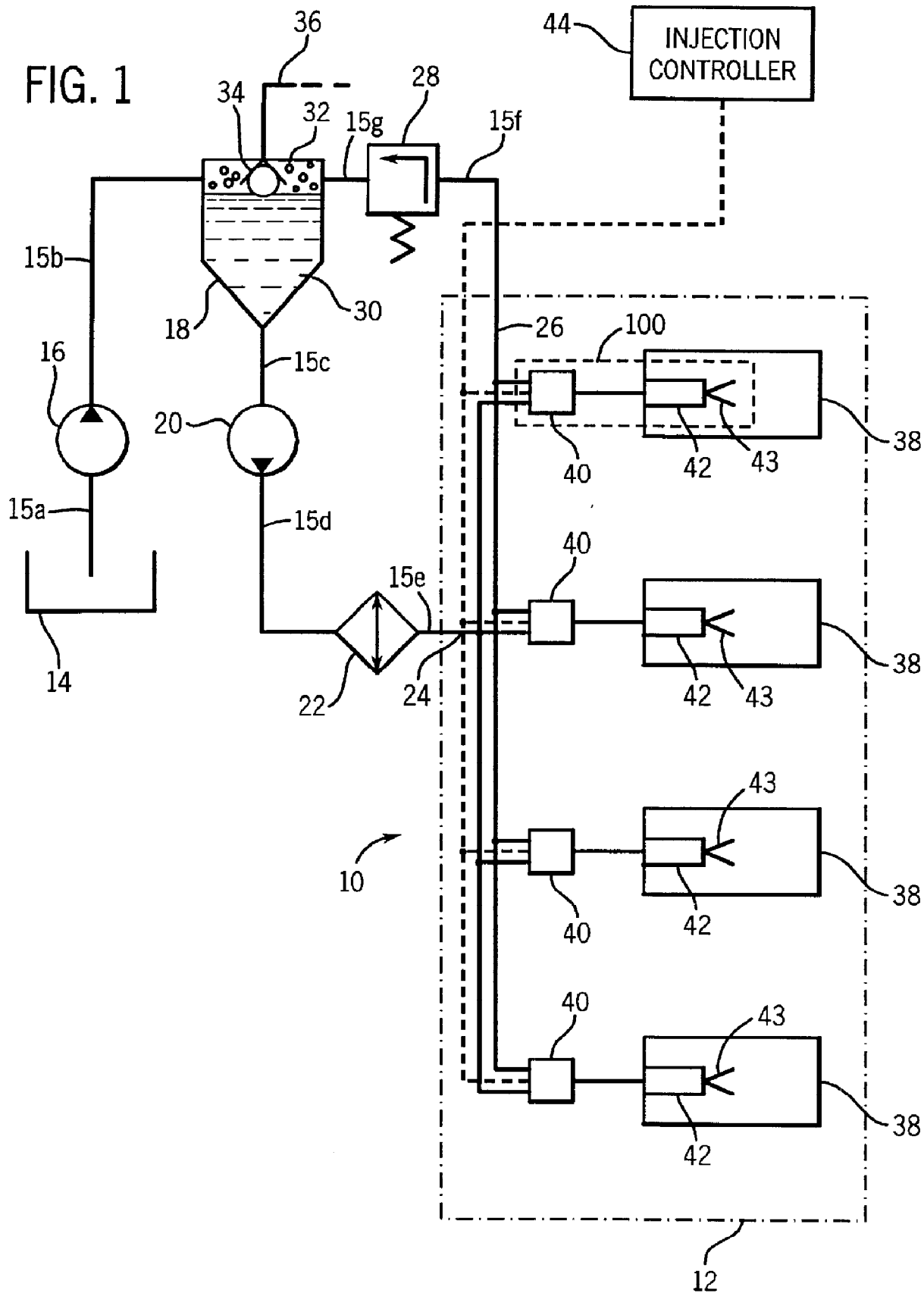


FIG. 2

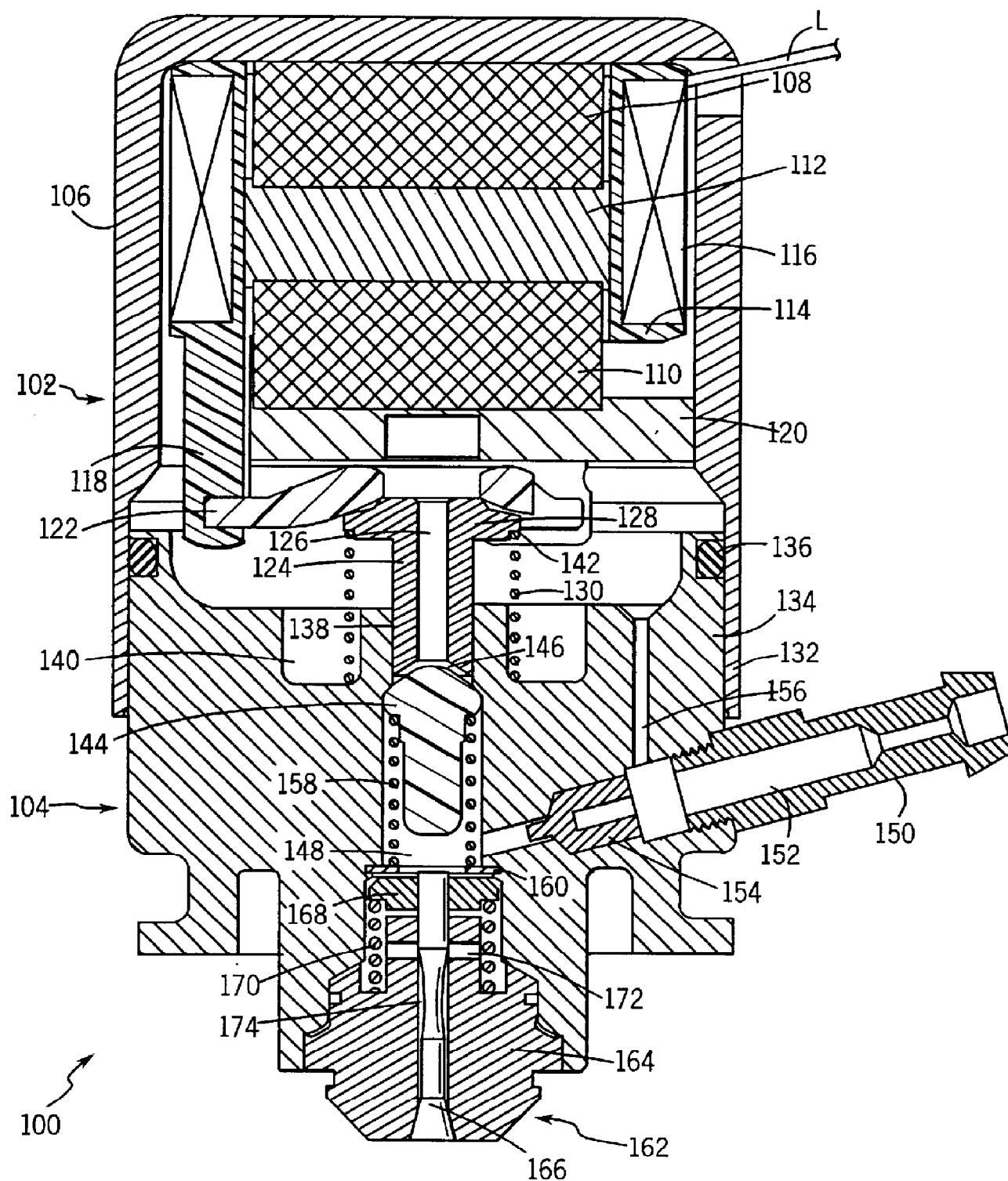


FIG. 3

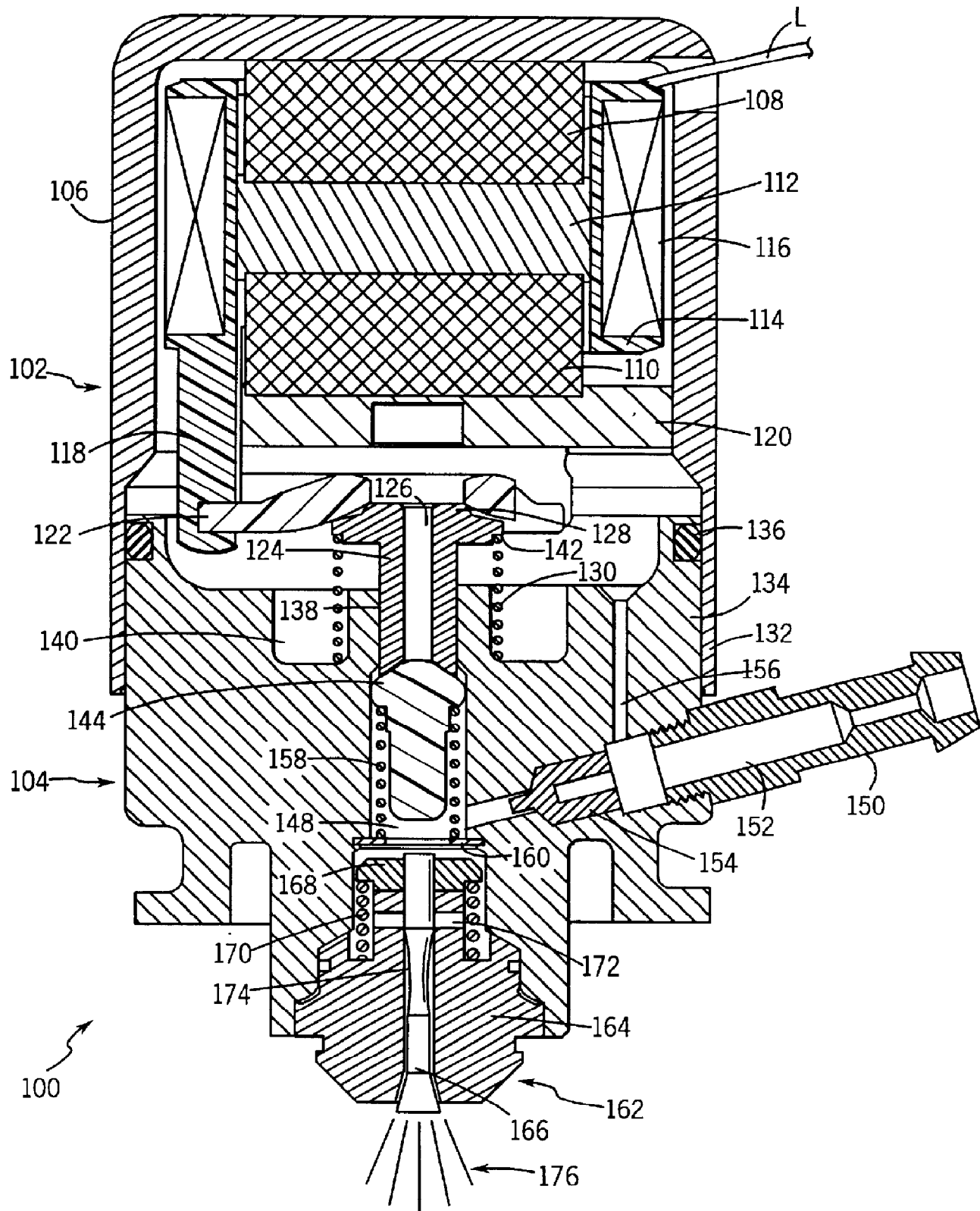


FIG. 4

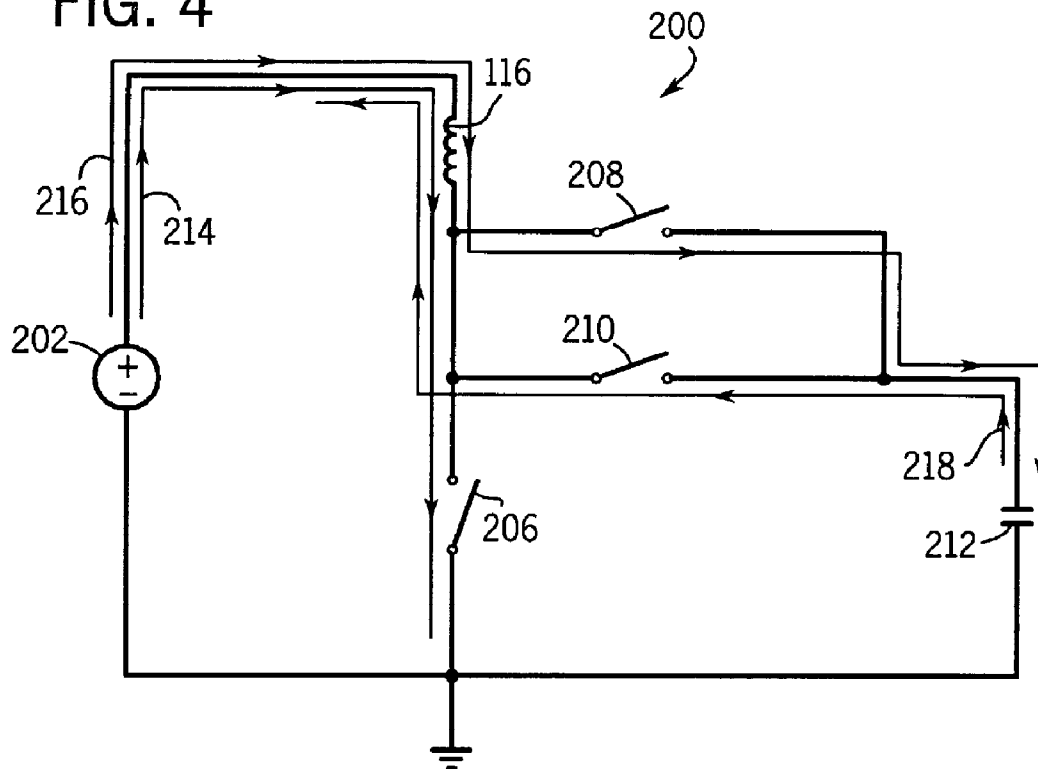


FIG. 5

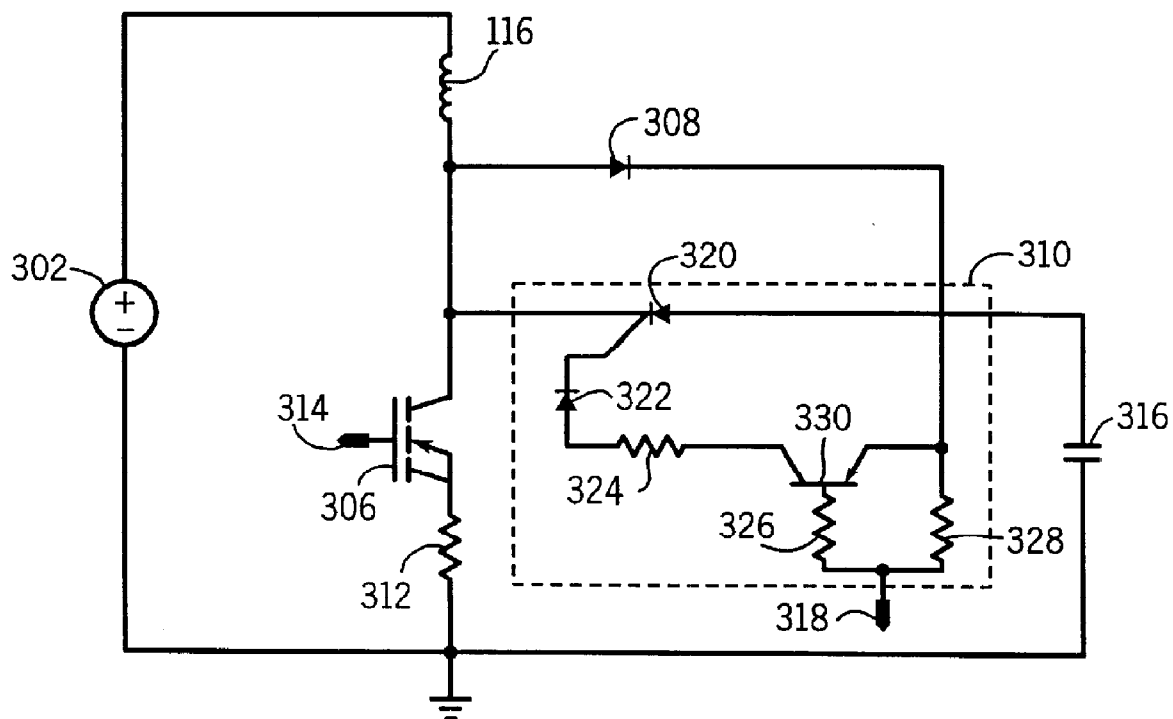
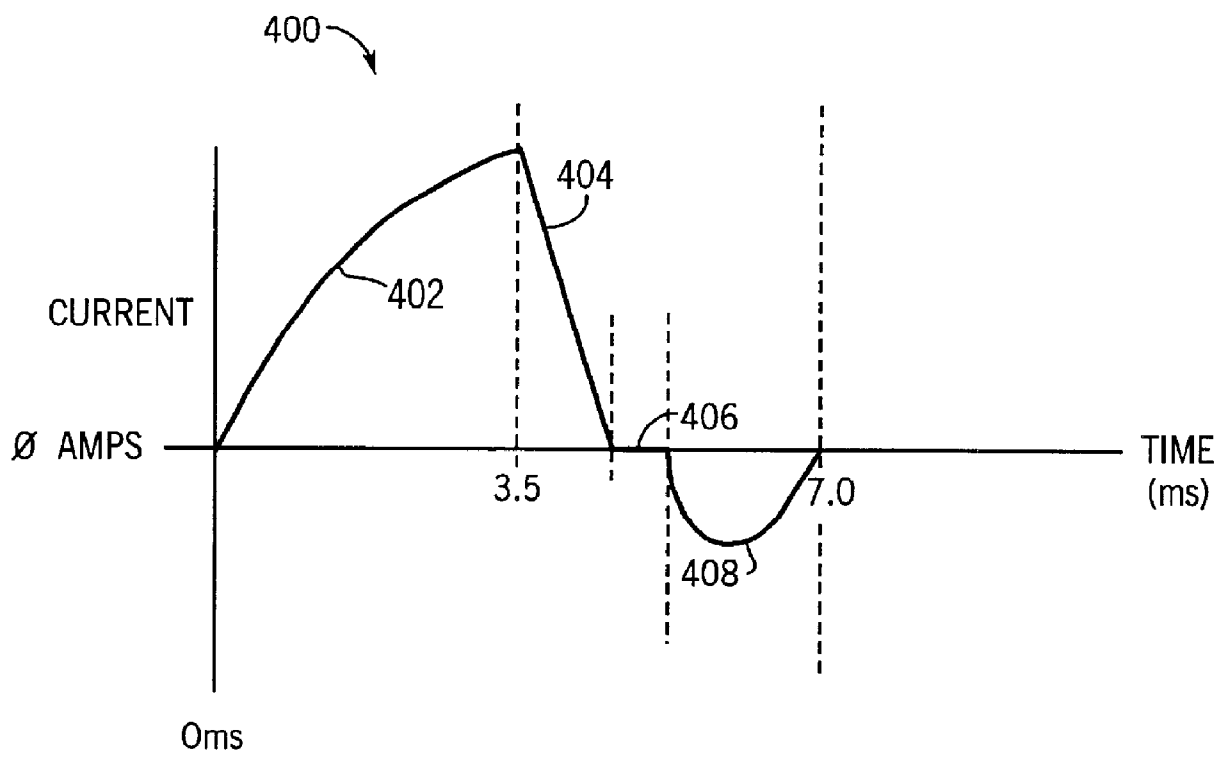


FIG. 6



FUEL INJECTION DRIVER CIRCUIT WITH ENERGY STORAGE APPARATUS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to an apparatus and method for delivering fuel for combustion in an internal combustion engine. More specifically, the present invention relates to an apparatus and method for increasing the speed of a fuel injector by using a capacitor to store energy which can be used to accelerate the rate at which an electro-

2. Description of the Related Art

A wide range of pumps have been developed for displacing fluids under pressure produced by electrical drives. For example, in certain fuel injection systems, fuel is displaced via a reciprocating pump assembly which is driven by electric current supplied from a source, typically a vehicle electrical system. In one fuel pump design of this type, a reluctance gap coil is positioned in a solenoid housing, and an armature is mounted movably within the housing and secured to a guide tube. The solenoid coil may be energized to force displacement of the armature toward the reluctance gap in a magnetic circuit defined around the solenoid coil. The guide tube moves with the armature, entering and withdrawing from a pump section. By reciprocal movement of the guide tube into and out of the pump section, fluid is drawn into the pump section and expressed from the pump section during operation.

In pumps of the type described above, the armature and guide tube are typically returned to their original position under the influence of one or more biasing springs. Where a fuel injection nozzle is connected to the pump, an additional biasing spring may be used to return the injection nozzle to its original position. Upon interruption of energizing current to the coil, the combination of biasing springs then forces the entire movable assembly to its original position. The cycle time of the resulting device is the sum of the time required for the pressurization stroke during energization of the solenoid coil, and the time required for returning the armature and guide to the original position for the next pressure stroke. Engine speed is generally a function of the flow rate of fuel to the combustion chamber. Increasing the speed of the engine shortens the duration of each combustion cycle. Thus, a fuel delivery system must provide the desired volumes of fuel for each combustion cycle at increasingly faster rates if the engine speed is to be increased.

Where such pumps are employed in demanding applications, such as for supplying fuel to combustion chambers of an internal combustion engine, cycle times can be extremely rapid. Cycle time refers to the amount of time required for a fuel injector to load with fuel, discharge the fuel into the combustion chamber and then return to its original position to start the cycle over again. Cycle time is typically short for fuel injectors. For example, injectors used in a direct injection system can obtain a cycle time of 0.01 seconds. That equates to the injectors being able to load with fuel, discharge the fuel into the combustion chamber, and then prepare to reload for a subsequent cycle 100 times in a single second. While this cycle time seems very short, it is often desirable to reduce this time even further when possible.

Moreover, repeatability and precision in beginning and ending of pump stroke cycles can be important in optimizing the performance of the engine under varying operating conditions. While the cycle time may be reduced by pro-

viding stronger springs for returning the reciprocating assembly to the initial position, such springs have the adverse effect of opposing forces exerted on the reciprocating assembly by energization of the solenoid. Such forces must therefore be overcome by correspondingly increased forces created during energization of the solenoid. At some point, however, increased current levels required for such forces become undesirable due to the limits of the electrical components, and additional heating produced by electrical losses.

There is a need, therefore, for an improved technique for pumping fluids in a linearly reciprocating fluid pump. There is a particular need for an improved technique for providing rapid cycle times in fluid pumps, such as fuel pumps without substantially increasing the forces and current demands of electrical driving components.

SUMMARY OF THE INVENTION

The present invention provides a novel technique for pumping fluids in a reciprocating pump arrangement designed to respond to these needs. The technique is particularly well suited for use in fuel delivery systems, such as in chamber fuel injection. However, the technique is in no way limited to such applications, and may be employed in a wide range of technical fields. The pumping drive system offers significant advantages over known arrangements, including a reduction in cycle times and so forth.

The technique is based upon a drive system employing at least one permanent magnet and at least one coil assembly. The coil assembly is energized cyclically by a reciprocating circuit to produce reciprocating motion of a drive member, which may be coupled directly to the coil. The drive member may extend into a pumping section, and cause variations in fluid pressure by intrusion into and withdrawal from the pumping section during its reciprocal movement. Valves, such as check valves, within the pumping section are actuated by the variations in pressure, permitting fluid to be drawn into the pumping section and expressed therefrom.

More specifically, the drive section has a reciprocating coil assembly to which alternating polarity control signals are applied by a reciprocating circuit. A permanent magnet structure of the drive section creates a magnetic flux field which interacts with an electromagnetic field produced during application of the control signals to the coil. Depending upon the polarity of the control signals applied to the coil, the coil is driven in one of two directions of movement. The reciprocating circuit employs a storage capacitor and several switches to capture the energy of the reciprocating coil as the pump is driven downwardly. The charge is recycled as the capacitor dissipates, thereby reversing the polarity of the current through the coil and driving the coil assembly upwardly to its initial position. A drive member transfers movement of the coil to a pump element which reciprocates with the coil to draw fluid into a pump chamber and expel the fluid during each pump cycle.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

FIG. 1 is a diagrammatical representation of a series of fluid pump assemblies applied to inject fuel into an internal combustion engine;

FIG. 2 is a partial sectional view of an exemplary pump in accordance with aspects of the present technique for use

in displacing fluid under pressure, such as for fuel injection into a chamber of an internal combustion engine as shown in FIG. 1;

FIG. 3 is a partial sectional view of the pump illustrated in FIG. 2 energized during a pumping phase of operation;

FIG. 4 is a circuit diagram illustrating a reciprocating circuit and current flow in accordance with the present invention;

FIG. 5 is an exemplary embodiment of the reciprocating circuit illustrated in FIG. 4; and

FIG. 6 is a current waveform corresponding to the reciprocating circuit illustrated in FIGS. 4 and 5.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Turning now to the drawings and referring first to FIG. 1, a fuel injection system 10 is illustrated diagrammatically, including a series of pumps for displacing fuel under pressure in an internal combustion engine 12. While the fluid pumps of the present technique may be employed in a wide variety of settings, they are particularly well suited to fuel injection systems in which relatively small quantities of fuel are pressurized cyclically to inject the fuel into combustion chambers of an engine as a function of the engine demands. The pumps may be employed with individual combustion chambers as in the illustrated embodiment, or may be associated in various ways to pressurize quantities of fuel, as in a fuel rail, feed manifold, and so forth. Even more generally, the present pumping technique may be employed in settings other than fuel injection, such as for displacing fluids under pressure in response to electrical control signals used to energize coils of a drive assembly, as described below.

In the embodiment shown in FIG. 1, the fuel injection system 10 includes a fuel reservoir 14, such as a tank for containing a reserve of liquid fuel. A first pump 16 draws the fuel from the reservoir through a first fuel line 15a, and delivers the fuel through a second fuel line 15b to a separator 18. While the system may function adequately without a separator 18, in the illustrated embodiment, separator 18 serves to insure that the fuel injection system downstream receives liquid fuel, as opposed to mixed phase fuel. A second pump 20 draws the liquid fuel from separator 18 through a third fuel line 15c and delivers the fuel, through a fourth fuel line 15d and further through a cooler 22, to a feed or inlet manifold 24 through a fifth fuel line 15e. Cooler 22 may be any suitable type of fluid cooler, including both air and liquid heater exchangers, radiators, and the like.

Fuel from the feed manifold 24 is available for injection into combustion chambers of engine 12, as described more fully below. A return manifold 26 is provided for recirculating fluid not injected into the combustion chambers of the engine. In the illustrated embodiment a pressure regulating valve 28 is coupled to the return manifold line 26 through a sixth fuel line 15f and is used for maintaining a desired pressure within the return manifold 26. Fluid returned via the pressure regulating valve 28 is recirculated into the separator 18 through a seventh fuel line 15g where the fuel collects in liquid phase as illustrated at reference numeral 30. Gaseous phase components of the fuel, designated by referenced numeral 32 in FIG. 1, may rise from the fuel surface and, depending upon the level of liquid fuel within the separator, may be allowed to escape via a float valve 34. The float valve 34 consists of a float that operates a ventilation valve coupled to a ventilation line 36. The ventilation line 36 is provided for permitting the escape of gaseous

components, such as for repressurization, recirculation, and so forth. The float rides on the liquid fuel 30 in the separator 18 and regulates the ventilation valve based on the level of the liquid fuel 30 and the presence of vapor in the separator 18.

Engine 12 includes a series of cylinders or combustion chambers 38 for driving an output shaft (not shown) in rotation. As will be appreciated by those skilled in the art, depending upon the engine design, pistons (not shown) are driven in a reciprocating fashion within each combustion chamber in response to ignition of fuel within the combustion chamber. The stroke of the piston within the chamber will permit fresh air for subsequent combustion cycles to be admitted into the chamber, while scavenging combustion products from the chamber. While the present embodiment employs a straightforward two-stroke engine design, the pumps in accordance with the present technique may be adapted for a wide variety of applications and engine designs, including other than two-stroke engines and cycles.

In the illustrated embodiment, a reciprocating pump 40 is associated with each combustion chamber 38, drawing pressurized fuel from the feed manifold 24, and further pressurizing the fuel for injection into the respective combustion chamber 38. A nozzle 42 is provided for atomizing the pressurized fuel downstream of each reciprocating pump 40. While the present technique is not intended to be limited to any particular injection system or injection scheme, in the illustrated embodiment, a pressure pulse created in the liquid fuel forces a fuel spray 43 to be formed at the mouth or outlet of the nozzle 42, for direct, in-cylinder injection. The operation of reciprocating pumps 40 is controlled by an injection controller 44. Injection controller 44, which will typically include a programmed microprocessor or other digital processing circuitry and memory for storing a routine employed in providing control signals to the pumps, applies energizing signals to the pumps to cause their reciprocation in any one of a wide variety of manners as described more fully below.

An exemplary reciprocating pump assembly, such as for use in a fuel injection system of the type illustrated in FIG. 1, is shown in FIGS. 2 and 3. Specifically, FIG. 2 illustrates a pump and nozzle assembly 100 which incorporates a pump driven in accordance with the present techniques. Assembly 100 essentially comprises a drive section 102 and a pump section 104. The drive section 102 is designed to cause reciprocating pumping action within the pump section 104 in response to application of reversed polarity control signals applied to an actuating coil of the drive section as described in greater detail below. The characteristics of the output of the pump section 104 may thus be manipulated by altering the waveform of the alternated polarity signal applied to the drive section 102. In the presently contemplated embodiment, the pump and nozzle assembly 100 illustrated in FIG. 2 is particularly well suited for application in an internal combustion engine, as illustrated in FIG. 1. Moreover, in the embodiment illustrated in FIG. 2, a nozzle assembly is installed directly at an outlet of the pump section 104, such that the pump 40 and the nozzle 42 of FIG. 1 are incorporated into a single assembly 100. As indicated above, in appropriate applications, the pump 40 may be separated from the nozzle 42, such as for application of fluid under pressure to a manifold, fuel rail, or other downstream component.

As illustrated in FIG. 2, drive section 102 includes a housing 106 designed to receive and support the drive section 102 during operation as well as to seal the components within the housing 106. The drive section 102 further

includes at least one permanent magnet **108**, and in the preferred embodiment illustrated, a pair of permanent magnets **108** and **110**. The permanent magnets **108** and **110** are separated from one another and disposed adjacent to a central core **112** made of a material which is capable of conducting magnetic flux, such as a ferromagnetic material. A coil bobbin **114** is disposed about permanent magnets **108** and **110** and core **112**. While magnets **108** and **110**, and core **112** are fixedly supported within housing **106**, bobbin **114** is free to slide longitudinally with respect to these components. That is, bobbin **114** is centered around core **112**, and may slide with respect to the core upwardly and downwardly in the orientation shown in FIG. 2. A coil **116** is wound within bobbin **114** and free ends of the coil are coupled to leads L for receiving energizing control signals, such as from an injection controller **44**, as illustrated in FIG. 1 and discussed further with reference to FIG. 4. Bobbin **114** further includes an extension **118** which protrudes from the region of the bobbin **114** in which the coil **116** is installed for driving the pump section **104**, as described below. Although one such extension is illustrated in FIG. 2, it should be understood that the bobbin **114** may comprise a series of extensions arranged circumferentially around the bobbin **114**. Finally, drive section **102** includes a support or partition **120** which aids in supporting the permanent magnets **108** and **110** and the central core **112**, and in separating the drive section **102** from the pump section **104**. It should be noted, however, that in the illustrated embodiment, the inner volume of the drive section **102**, including the volume in which the coil **116** is disposed, may be flooded with fluid during operation, such as for cooling purposes.

A drive member **122** is secured to bobbin **114** via extension **118**. In the illustrated embodiment, drive member **122** forms a generally cup-shaped plate having a central aperture for the passage of fluid. The cup shape of the drive member **122** aids in centering a plunger **124** which is disposed within a concave portion of the drive member **122**. Plunger **124** preferably has a longitudinal central opening or aperture **126** extending from its base to a head region **128** designed to contact and bear against drive member **122**. A biasing spring **130** is compressed between the head region **128** and a lower component of the pump section **104** to maintain the plunger **124**, the drive member **122**, and bobbin **114** and coil **116** in an upward or biased position. As will be appreciated by those skilled in the art, plunger **124**, drive member **122**, extension **118**, bobbin **114**, and coil **116** thus form a reciprocating assembly which is driven in an oscillating motion during operation of the device as described more fully below.

The drive section **102** and pump section **104** are designed to interface with one another, preferably to permit separate manufacturing and installation of these components as sub-assemblies and to permit their servicing, as needed. In the illustrated embodiment, housing **106** of drive section **102** terminates in a skirt **132** which is secured about a peripheral wall **134** of pump section **104**. The drive and pump sections **102** and **104** are preferably sealed, such as via a soft seal **136**. Alternatively, these housings maybe interfaced via threaded engagement, or any other suitable technique.

Pump section **104** forms a central aperture **138** designed to receive plunger **124**. Aperture **138** also serves to guide the plunger in its reciprocating motion during operation of the device. An annular recess **140** surrounds aperture **138** and receives biasing spring **130**, maintaining the biasing spring **130** in a centralized position to further aid in guiding plunger **124**. In the illustrated embodiment, head region **128** includes a peripheral groove or recess **142** which receives biasing spring **130** at an end opposite recess **140**.

A valve member **144** is positioned in pump section **104** below plunger **124**. In the illustrated embodiment, valve member **144** forms a separable extension of plunger **124** during operation, but is spaced from plunger **124** by a gap **146** when plunger **124** is retracted as illustrated in FIG. 2. Gap **146** is formed by limiting the upward movement of valve member **144**, such as by a restriction in the peripheral wall defining aperture **138**. Grooves (not shown) may be provided at this location to allow for the flow of fluid around valve member **144** when the plunger is advanced to its retracted position. As described more fully below, gap **146** permits the entire reciprocating assembly, including plunger **124**, to gain momentum during a pumping stroke before contacting valve member **144** to compress and expel fluid from the pump section.

Valve member **144** is positioned within a pump chamber **148**. Pump chamber **148** receives fluid from an inlet **150**. Inlet **150** thus includes inlet passage **152** through which fluid, such as pressurized fuel, is introduced into the pump chamber **148**. A check valve assembly, indicated generally at reference numeral **154**, is provided between inlet passage **152** and pump chamber **148**, and is closed by the pressure created within pump chamber **148** during a pumping stroke of the device. In the illustrated embodiment, a fluid passage **156** is provided between inlet passage **152** and the volume within which the drive section **102** components are disposed. Fluid passage **156** may permit the free flow of fluid into the drive section **102**, to maintain that the drive section components bathed in fluid. A fluid outlet (not shown) may similarly be in fluid communication with the internal volume of the drive section **102**, to permit the recirculation of fluid from the drive section **102**. Valve member **144** is maintained in a biased position toward gap **146** by a biasing spring **158**. In the illustrated embodiment, biasing spring **158** is compressed between an upper portion of the valve member **144** and a retaining ring **160**.

When the pump defined by the components described above is employed for direct fuel injection, as one exemplary utilization, a nozzle assembly **162** may be incorporated directly into a lower portion of the pump assembly **104**. As shown in FIG. 2, an exemplary nozzle assembly **162** includes a nozzle body **164** which is sealingly fitted to the pump section **104**. A poppet **166** is positioned within a central aperture formed in the valve body, and is sealed against the valve body in a retracted position. At an upper end of poppet **166**, a retaining member **168** is provided. Retaining member **168** contacts a biasing spring **170** which is compressed between the nozzle body **164** and the retaining member **168** to maintain the poppet **166** in a biased, sealed position within the nozzle body **164**. Fluid is free to pass from pump chamber **148** into the region surrounding the retaining member **168** and spring **170**. This fluid is further permitted to enter into passages **172** formed in the nozzle body **164** around poppet **166**. An elongated annular flow path **174** extends from passages **172** to the sealed end of the poppet **166**. As will be appreciated by those skilled in the art, other components may be incorporated into the drive section **102**, the pump section **104**, or the nozzle assembly **162**. For example, where desired, an outlet check valve may be positioned at the exit of pump chamber **148** to isolate a downstream region from the pump chamber.

FIG. 3 illustrates the pump and nozzle assembly of FIG. 2 in an actuated position. As shown in FIG. 3, upon application of energizing current to the coil **116**, the coil **116**, bobbin **114**, extension **118**, and drive member **122** are displaced downwardly. This downward displacement is the result of interaction between the electromagnetic field sur-

rounding coil **116** by application of the energizing current thereto, and the magnetic field present by virtue of permanent magnets **108** and **110**. In the preferred embodiment, this magnetic field is reinforced and channeled by core **112**. As drive member **122** is forced downwardly by interaction of these fields, it contacts plunger **124** to force the plunger downwardly against the resistance of spring **130**. During an initial phase of this displacement, plunger **142** is free to extend into pump chamber **148** without contact with valve member **144**, by virtue of gap **146** (see FIG. 2). Plunger **142** thus gains momentum, and eventually contacts the upper surface of valve member **144**. The lower surface of plunger **124** seats against and seals with the upper surface of valve member **144**, to prevent flow of fluid upwardly through passage **126** of the plunger **142**, or between the plunger **142** and the aperture **138** of the pump section **104**. Further downward movement of the plunger **142** and valve member **144** begin to compress fluid within pump chamber **148**, closing inlet check valve **154**.

Still further movement of the plunger **142** and the valve member **144** produces a pressure surge or spike which is transmitted downstream, such as to nozzle assembly **162**. In the illustrated embodiment, this pressure surge forces poppet **166** to unseat from the nozzle body **164**, moving downwardly with respect to the nozzle body **164** by a compression of spring **170** between retainer **168** and the nozzle body **164**. Fluid **176**, such as fuel, is thus sprayed or released from the nozzle **162**, such as directly into a combustion chamber of an internal combustion engine as described above with reference to FIG. 1.

As will be appreciated by those skilled in the art, upon reversal of the polarity of the drive or control signal applied to coil **116** through the leads L, an electromagnetic field surrounding the coil **116** will reverse in orientation, causing an oppositely oriented force to be exerted on the coil **116** by virtue of interaction between this field and the magnetic field produced by magnets **108** and **110**. This force will thus drive the coil **116**, and other components of the reciprocating assembly back toward their original position (shown in FIG. 2). In the illustrated embodiment, as drive member **122** is driven upwardly back towards the position illustrated in FIG. 2, spring **130** urges plunger **128** upwardly towards its original position, and spring **158** similarly urges valve member **144** back towards its original position. Gap **126** is reestablished as illustrated in FIG. 2, and a new pumping cycle may begin. Where a nozzle **162** such as that shown in FIGS. 2 and 3 is provided, the nozzle **162** is similarly closed by the force of spring **170**. In this case, as well as where no such nozzle is provided, or where an outlet check valve is provided at the exit of pump chamber **148**, pressure is reduced within pump chamber **148** to permit inlet check valve **154** to reopen for introduction of fluid for a subsequent pumping cycle.

By appropriately configuring drive signals applied to coil **116** through the leads L, the device of the present invention may be driven in a wide variety of manners. FIG. 4 shows a basic circuit in accordance with the present invention. The circuit **200** provides a means for driving the electro-mechanical solenoid, used here in a fuel injector, which provides for an accelerated reciprocal motion of the drive member **122** illustrated in FIGS. 2 and 3. The voltage source **202** is used to provide the current flow to the coil **116** through leads L illustrated in FIGS. 2 and 3. Also coupled to the coil **116** is a series of switches **206**, **208**, and **210**. The switches **206**, **208**, and **210** are arranged to allow a capacitor **212** to store voltage to provide a reverse current through the circuit which will facilitate a faster reciprocal motion of the

drive member **122** (shown in FIGS. 2 and 3), as discussed below. Initially, the first switch **206** is closed and the second and third switches **208** and **210** are open. When voltage is applied by the source **202**, a current flows in the path indicated by current path **214**. Because the first switch **206** is closed, it provides a path to ground and thus the current **214** will flow from the voltage source **202** through the coil **116** through the closed switch **206** and to ground. This actuates the coil **116**, converting the electrical energy produced by the voltage source **202** into a linear motion of the drive member **122** which operates the fuel injection system, as described with reference to FIGS. 2 and 3.

Next, the first switch **206** is opened thereby producing a voltage across the coil **116**. At this time, the second switch **208** is closed. The current flows from the voltage source **202** as indicated by current path **216**. The current **216** flows from the voltage source **202** through the coil **116**, through the second switch **208** and through the capacitor **212**. At this time, the voltage which was stored in the coil **116** will be transferred and stored in the capacitor **212**. Depending on the energy stored in the coil **116** at the time the second switch **208** is closed, and depending upon size of the capacitor **212**, the voltage magnitude in the capacitor **212** will vary. Once the voltage of the capacitor **212** reaches a predetermined voltage, the second switch **208** is opened and the third switch **210** is closed. This situation will be triggered when the voltage stored in the capacitor **212** becomes higher than the voltage produced by the source **202**. The current now flows through the circuit as indicated by flow path **218**. The current **218** flows from the capacitor **212** through the third switch **210** and back through the coil **116**. This reverse current will push the drive member **122** back to its original position as indicated in FIG. 2.

By using a reverse current **218** to provide reciprocal motion of the drive member **122** in accordance with the embodiment described herein, several advantages over prior electro-mechanical solenoid based systems, such as fuel injectors, may be achieved. First, as previously discussed and as will be discussed with reference to FIG. 6, the cycle time for fuel injection may be reduced. Second, because the system is recycling the energy by storing energy from the coil **116** in a capacitor **212** and then recycling that energy to produce the reciprocal motion of the drive member **122**, the power consumption of the injection system may be reduced. Third, there is a reduction in the power dissipation in the first switch **206**.

FIG. 5 illustrates one specific embodiment of a circuit incorporating the present technique. It should be noted however that any suitable substitutes for the particular elements shown in FIG. 5 may be used. FIG. 5 illustrates a voltage source **302** which may be a 55 volt source. The voltage source **302** is coupled to one lead of the coil **116**. The second lead of the coil **116** is coupled to the switches **306**, **308**, and **310**. The first switch in the embodiment illustrated in FIG. 5 is an n-channel MOSFET **306**. The drain of the MOSFET **306** is coupled to the second lead of the coil **116**. The source of the MOSFET **306** is coupled to ground through a resistor **312**. The gate of the MOSFET **306** is coupled to a micro-controller **314** as discussed in FIG. 1 with reference to injection controller **44**.

As discussed with reference to FIG. 4, initially, the first switch **306** is closed and thus current flows from the voltage source **302** through the coil **116**, through the MOSFET **306**, and to ground. The micro-controller **314** will then turn the MOSFET **306** off thereby opening the gate and facilitating the storage of energy within the coil **116**. In this particular embodiment, the second switch is illustrated as a diode **308**.

In this configuration, the current will initially flow through the diode **308** once the coil **116** builds a charge of over 0.7 volts. One advantage of using a diode **308** as a second switch is that the current will automatically flow through the diode **308** once the coil **116** reaches a certain threshold voltage above the voltage of the capacitor **316**. Here, the voltage in the coil **116** only needs to be 0.7 volts above the voltage in the capacitor **316** to activate the switch. By having an automatic activation, switch **308** does not need to be coupled to a micro-controller. This may reduce the cost of the circuit and the complexity of the design. However, it should be evident that any configuration may be used such that the switch closes when the voltage in the coil **116** reaches some greater threshold above the voltage in the capacitor **316**.

Energy is stored in the capacitor **316** until such time that micro-controller **318** closes the third switch **310**. At this point, the voltage stored in the capacitor **316** will be driven back to the coil **116** thereby facilitating the reciprocating motion of the drive member **122** (shown in FIGS. **2** and **3**) at an increased speed. Here, the third switch **310** is constructed using diodes **320** and **322**, resistors **324**, **326** and **328**, and transistor **330**. However, it should be evident again that any preferred switching circuit may be used for the switch **310**.

FIG. **6** illustrates a current waveform in accordance with the embodiment illustrated in FIGS. **4** and **5**. The typical cycle time for an injection cycle is greater than 10 ms. The present embodiment however, enables an injection time of 1–7 ms as further discussed below. A waveform **400** is illustrated over time in FIG. **6**. The first segment **402** of the waveform **400** illustrates the fuel injection event corresponding to current path **214** in FIG. **4**. The cycle time for the fuel injection event according to the present embodiment is generally less than 3.5 ms. The second segment **404** of the curve **400** illustrates the capacitor charging as the energy from the fuel injector coil is dissipated into the capacitor, as indicated by current path **216** in FIG. **4**. There may be some amount of time **406** along the curve between the time that the capacitor is charging **404** and when the capacitor is discharging through the fuel injector in a reverse direction as illustrated by curve segment **408**. The time it takes for the capacitor to charge from the power dissipation from the coil and for the capacitor to discharge back to the coil to enable the reciprocal motion of the drive member may vary depending on the engine capabilities and the speed of the motor. In the present embodiment, however the cycle time may be less than 3.5 ms.

While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.

What is claimed is:

1. A reciprocating fuel pump system comprising:

a housing assembly including a drive section and a pump section;

a drive assembly disposed in the drive section, the drive assembly including a permanent magnet and a coil assembly having a winding comprising a first lead and a second lead and disposed within the central volume of the drive section adjacent to the permanent magnet and movable reciprocally axially along a central axis upon application of alternating current power to the winding;

a pump member secured to and movable reciprocally with the coil assembly, the pump member extending into the pump section to produce pressure variations in the pump section during reciprocal movement to draw fuel into the pump section and to express fuel therefrom; and

a reciprocating circuit coupled to the coil assembly and including a storage capacitor and a plurality of switches, the first lead of the coil assembly coupled to the voltage source and the second lead of the coil assembly coupled to the storage capacitor through at least one of the plurality of switches.

2. The pump system of claim **1**, wherein the permanent magnet at least partially surrounds a portion of the central volume and extends generally along a central axis, and wherein the coil assembly is disposed radially within the portion of the central volume.

3. The pump system of claim **1**, wherein the permanent magnet is disposed adjacent to an end of the drive section, and wherein the coil assembly is disposed between the permanent magnet and the pump section.

4. The pump system of claim **1**, wherein the permanent magnet includes at least one magnet elements.

5. The pump system of claim **1**, wherein the pump member includes a tubular member extending from the coil assembly through a sealed bore into the pump section.

6. The pump system of claim **1**, wherein the pump section includes an inlet check valve and an outlet check valve, the inlet and outlet check valves being actuated by pressure variations produced by reciprocal movement of the pump member in the pump section.

7. The pump system of claim **1**, further comprising a nozzle in fluid communication with the pump section for expressing pressurized fuel from the pump section.

8. The pump system of claim **1**, wherein the reciprocating circuit comprises a first switch, a second switch, and a third switch.

9. The pump system of claim **8**, wherein the first switch is arranged in parallel with the second switch and further in parallel with the third switch.

10. The pump system of claim **8**, wherein the reciprocating circuit is configured such that the coil assembly is in series between this voltage source and the plurality of switches.

11. The pump system of claim **10**, wherein the reciprocating circuit is further configured such that the coil assembly is in series with each of the first switch, the second switch, and the third switch.

12. The pump system of claim **11**, wherein the first switch is coupled to ground.

13. The pump system of claim **12**, wherein the capacitor is coupled in series between the second switch and ground.

14. The pump system of claim **13**, wherein the second switch comprises a diode.

15. The pump system of claim **14**, wherein the first switch is coupled to a micro-controller.

16. The pump system of claim **15**, wherein the third switch is coupled to a micro-controller.

17. A reciprocating fuel pump comprising:

a resonant drive system including a resonant coil assembly having a first lead and a second lead and a permanent magnet, one of the resonant coil assembly and the permanent magnet being disposed in a fixed position and the other of the resonant coil assembly and permanent magnet being movable reciprocally by application of electrical current from a reciprocating circuit coupled to the coil assembly, the reciprocating circuit

including a storage capacitor and a plurality of switches, the first lead of the coil assembly coupled to a voltage source and the second lead of the coil assembly coupled to the storage capacitor through at least one of the plurality of switches, to the resonant coil assembly, the drive system Her comprising a drive member secured to and movable reciprocally with either the coil assembly or the permanent magnet;

a pump assembly adjacent to the drive system, the drive member extending into the pump assembly for generating increases and decreases in fluid pressure within the pump assembly during reciprocal movement to draw fuel into the pump assembly and to express fuel therefrom.

18. The pump of claim 17, wherein the permanent magnet is disposed in a fixed location within the drive system at least partially surrounding a central volume thereof and extending generally along a central axis, and wherein the coil assembly is disposed movably within the portion of the central volume.

19. The pump of claim 17, wherein the permanent magnet is disposed in a fixed location adjacent to an end of the drive system, and wherein the coil assembly is disposed between the permanent magnet and the pump assembly.

20. The pump of claim 17, wherein the permanent magnet includes at least one magnet elements.

21. The pump of claim 17, wherein the drive member includes a tubular member extending from the coil assembly through a sealed bore into the pump assembly.

22. The pump of claim 17, wherein the pump assembly includes an inlet check valve and an outlet check valve, the inlet and outlet check valves being actuated by pressure variations produced by reciprocal movement of the drive member during operation.

23. The pump of claim 17, further comprising a nozzle in fluid communication with the pump assembly for expressing pressurized fuel from the pump assembly.

24. The pump of claim 17, wherein the reciprocating circuit comprises a first switch, a second switch, and a third switch.

25. The pump of claim 24, wherein the first switch is arranged in parallel with the second switch and further in parallel with the third switch.

26. The pump of claim 24, wherein the reciprocating circuit is configured such that the coil assembly is in series between the voltage source and the plurality of switches.

27. The pump of claim 26, wherein the reciprocating circuit is further configured such that the coil assembly is in series with each of the first switch, the second switch, and the third switch.

28. The pump of claim 27, wherein the first switch is coupled to ground.

29. The pump of claim 28, wherein the capacitor is coupled in series between the second switch and ground.

30. The pump of claim 29, wherein the second switch comprises a diode.

31. The pump of claim 30, wherein the first switch is coupled to a micro-controller.

32. The pump of claim 31, wherein the third switch is coupled to a micro-controller.

33. A reciprocating pump comprising:

a drive system including a permanent magnet and a resonant coil assembly, the coil assembly having a first lead and a second lead and being energizable by application of electrical current from a reciprocating circuit coupled to the coil assembly, the reciprocating circuit including a storage capacitor and a plurality of

switches, the first lead of the coil assembly coupled to a voltage source and the second lead of the coil assembly coupled to the storage capacitor through at least one of the plurality of switches to cause reciprocal movement of a drive member; and

a pump assembly disposed adjacent to the drive system, the pump assembly including means for admitting a supply of fluid into an inner volume of the pump assembly, means for pressurizing the inner volume by reciprocal movement of the drive member, and means for expressing pressurized fluid from the inner volume.

34. The pump of claim 33, wherein the permanent magnet is disposed in a fixed location within the drive system at least partially surrounding a central volume thereof and extending generally along a central axis, and wherein the coil assembly is disposed movably within the portion of the central volume.

35. The pump of claim 33, wherein the permanent magnet is disposed in a fixed location adjacent to an end of the drive system, and wherein the coil assembly is disposed between the permanent magnet and the pump assembly.

36. The pump of claim 33, wherein the permanent magnet includes at least two magnet elements.

37. The pump of claim 33, wherein the drive member includes a tubular member extending from the coil assembly through a sealed bore into the pump assembly.

38. The pump of claim 33, wherein the means for admitting a supply of fluid into an inner volume of the pump assembly includes a check valve biased into an open position and closed by an increase in pressure within the inner volume during operation.

39. The pump of claim 33, wherein the means for pressurizing the inner volume by reciprocal movement of the drive member includes a portion of the drive member.

40. The pump of claim 39, wherein the drive member is a tubular element and the means for pressurizing the inner volume includes a valve element which seats to seal an inner passageway of the drive member during a pressure stroke thereof.

41. The pump of claim 33, wherein the means for expressing pressurized fluid from the inner volume includes an outlet check valve biased into a closed position and opened by an increase in pressure within the inner volume during operation.

42. The pump of claim 33, further comprising a nozzle in fluid communication with the pump assembly for expressing pressurized fluid from the pump assembly.

43. The pump of claim 33, wherein the reciprocating circuit comprises a first switch, a second switch, and a third switch.

44. The pump of claim 43, wherein the first switch is arranged in parallel with the second switch and further in parallel with the third switch.

45. The pump of claim 43, wherein the reciprocating circuit is configured such that the coil assembly is in series between the voltage source and the plurality of switches.

46. The pump of claim 45, wherein the reciprocating circuit is further configured such that the coil assembly is in series with each of the first switch, the second switch, and the third switch.

47. The pump of claim 46, wherein the first switch is coupled to ground.

48. The pump of claim 47, wherein the capacitor is coupled in series between the second switch and ground.

49. The pump of claim 48, wherein the second switch comprises a diode.

50. The pump of claim 49, wherein the first switch is coupled to a micro-controller.

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51. The pump of claim 50, wherein the third switch is coupled to a micro-controller.

52. A method of producing a reciprocal motion in a fuel pump comprising the steps of:

- (a) providing a first, a second, and a third switch; 5
- (b) closing the first switch, opening the second switch, and opening the third switch;
- (c) producing a current using a voltage source;
- (e) providing a path from the voltage source to ground through a coil assembly and through the first switch; 10
- (e) opening the first switch;
- (f) storing a charge in the coil assembly;
- (g) providing a path from the voltage source to ground through the coil assembly through the second switch and through a capacitor; 15
- (h) closing the second switch;
- (i) discharging the energy stored in the coil assembly into the capacitor; 20
- (j) storing the energy in the capacitor;
- (k) opening the second switch and closing the third switch;
- (l) discharging the energy stored in the capacitor into the coil assembly. 25

53. A method of displacing fuel in a pump system comprising the steps of:

- (a) positioning a reluctance gap coil within a solenoid housing;

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(b) mounting an armature moveably within a housing and securing the armature to a guiding member;

(c) energizing the coil by providing a current through the coil in a first direction;

(d) actuating the coil to drive the armature in a downward direction toward a reluctance gap;

(e) de-energizing the coil by providing a first electrical path from the coil to a capacitor which is configured to store the energy which is dissipated from the coil;

(f) de-energizing the capacitor by providing a second electrical path from the capacitor to the coil by which current is driven through the coil in a second direction; and

(g) actuating the coil to drive the armature in an upward direction away from the reluctance gap.

54. A method of displacing a pumping assembly comprising the steps of:

(a) energizing a coil assembly to displace a pumping assembly in a first direction;

(b) storing energy in a capacitor coupled to the coil assembly; and

(c) discharging the energy from the capacitor to the coil assembly to displace the pumping assembly in a second direction opposite from the first direction.

55. The method of claim 54, wherein the energy is first stored in the coil assembly, and then discharged from the coil assembly to charge the capacitor.

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