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.
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 electromechanical solenoid returns to its initial position.

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 reciprocation 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 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 providing 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 reciprocation movement. Valves, such as check valves, within the pumping section are actuated by the variances 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 insulate the fuel injection system downstream from pressurized fluid, 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 recirculated 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 or 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 a shaft 108 which is operated to reciprocate the fluid within the pump section 104.
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 such an 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 upright 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 may be interlaced 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 surrounding the coil 116 and the permanent magnets 108 and 110. The downward displacement of the drive member 122 is communicated to the plunger 124, which in turn moves the fluid through the pump assembly.

FIG. 4 illustrates the impact of the energized current on the plunger 124, which in turn moves the fluid through the pump assembly. The movement of the plunger 124 is communicated to the drive member 122, which in turn moves the fluid through the pump assembly. The movement of the drive member 122 is communicated to the plunger 124, which in turn moves the fluid through the pump assembly. The movement of the plunger 124 is communicated to the drive member 122, which in turn moves the fluid through the pump assembly. The movement of the drive member 122 is communicated to the plunger 124, which in turn moves the fluid through the pump assembly.
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rounding coil 116 by application of the energizing current thereto, and the magnetic field present by virtue of perma-
nent 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 begins 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 174, 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
simultaneously driven upwardly back towards the position illustrated in
FIG. 2, spring 130 urges plunger 128 upwardsly towards its
original position, and spring 158 similarly urges valve member
144 back towards its original position. Gap 126 is
re-established 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 reciprocating 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 reciprocating 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 pro-
duced 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


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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 reciprocating 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 reciprocation movement to suck 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 reciprocation 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 the 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 system 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 moveable reciprocally by application of electrical current from a reciprocating circuit coupled to the coil assembly, the reciprocating circuit comprising a storage capacitor and a plurality of switches, each switch coupled to the resonant coil assembly and including a third lead coupled to the storage capacitor; and a pump member secured to and moveable reciprocally with the coil assembly, the pump member extending into the pump section to produce pressure variations in the pump section during reciprocation movement to suck 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.
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 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 fluid 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 element.

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.
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;
   (b) closing the first switch, opening the second switch, and opening the third switch;
   (c) producing a current using a voltage source;
   (d) providing a path from the voltage source to ground through a coil assembly and through the first switch;
   (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;
   (h) closing the second switch;
   (i) discharging the energy stored in the coil assembly into the capacitor;
   (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.

53. A method of displacing fuel in a pump system comprising the steps of:
   (a) positioning a reluctance gap coil within a solenoid housing;
   (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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