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(54) **Injector system**

(57) An injector system includes at least first and second injectors (22a, 22b), preferably of the piezoelectric type, and an injector drive control circuit. The drive control circuit (24) comprises select switch means (S1, S2) for controlling independent selection of the first or second injector (22a, 22b) to permit a discharging current to be supplied to the selected injector during a discharging mode so as to initiate an injection event, and charge/discharge switch means (Q1, Q2) for controlling whether the discharging current is supplied to the selected injector (22a, 22b) or whether a charging current is supplied to the selected injector during a charging mode so as to terminate the injection event. The first and second injectors (22a, 22b) are arranged electrically in parallel and operatively connected to the select and charge/discharge switch means (S1, S2, Q1, Q2) so that activation of the charge/discharge switch means to terminate the injection event results in respective voltages across the first and second injectors tending to equalise.

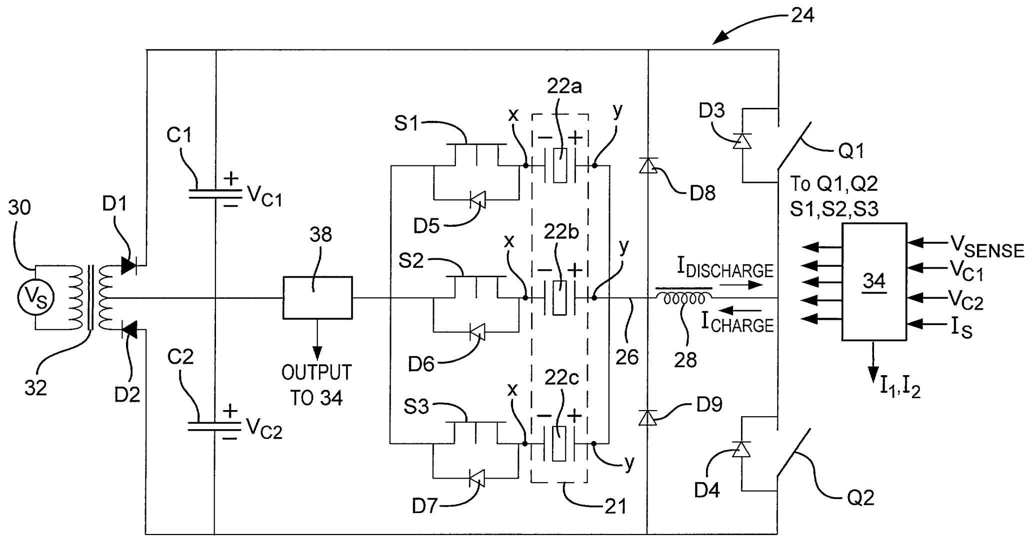

Fig.3

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Description

[0001] The invention relates to an injector system for an internal combustion engine, the injector system including a plurality of injectors of the type having a piezoelectric actuator for controlling injector valve needle movement. The invention also relates to a method of controlling an injector system incorporating a plurality of piezoelectric injectors.

[0002] Automotive vehicle engines are generally equipped with fuel injectors for injecting fuel (e.g. gasoline or diesel fuel) into the individual cylinders or intake manifold of the engine. The fuel injectors are coupled to a fuel rail containing high pressure fuel that is delivered by way of a fuel delivery system. The injectors typically employ a valve needle that is actuated to open and close so as to control the amount of high pressure fuel metered from the fuel rail and injected into the corresponding engine cylinder or intake manifold.

[0003] One type of fuel injector that offers precise metering of fuel is the piezoelectric fuel injector. Piezoelectric fuel injectors employ piezoelectric actuators including a stack of piezoelectric elements. With a piezoelectric fuel injector, the metering of fuel is generally achieved by controlling the electrical voltage potential, or charge, applied to the piezoelectric elements so as to vary the degree to which the stack extends and contracts. The extent of expansion and contraction of the piezoelectric elements varies the extent and direction of travel of the valve needle, towards and away from a valve needle seating, so as to control the duration for which injection occurs at a given fuel pressure. Control of the piezoelectric actuator therefore controls the fuel delivery quantity.

[0004] In order to inject fuel, so as to provide an "injection event", the piezoelectric actuator undergoes a discharge and a charge phase. In one type of piezoelectric injector (positive-charge displacement injectors), the injector is configured such that charging of the actuator stack causes the needle to lift away from the valve needle seating to start the injection event, with discharging of the actuator stack causing the needle to seat to end the injection event. In another type of piezoelectric injector (negative-charge displacement injectors) it is discharging of the actuator stack that causes the needle to lift, with charging of the stack causing the valve needle to seat. The injector is said to be "opened" when injection occurs, and "closed" when injection does not occur.

[0005] One problem which has been encountered in negative-charge displacement injectors is that, at the end of an injection event when the piezoelectric actuator is re-charged to close the injector, a degree of voltage overshoot occurs. The recharging voltage is applied to the actuator for a pre-determined duration, to ensure the voltage across the actuator reaches a threshold voltage level, V_{CHARGE}, at which the actuator causes the injector to close. However, in practice, certain system factors may cause continued extension of the piezoelectric stack for a short period of time after this calculated duration. This leads to a fluctuation of the voltage across the stack about the desired voltage level, V_{CHARGE}, an effect referred to as "voltage ringing". Positive voltage ringing occurs where the voltage across the stack is caused to exceed the threshold level, V_{CHARGE}, and negative voltage ringing occurs where the voltage across the stack is caused to fall below the threshold level, V_{CHARGE}. The effects of voltage ringing are disadvantageous as they reduce the accuracy with which the injector can be controlled and thus compromise injector efficiency.

[0006] A further problem with piezoelectric fuel injectors is that they require relatively high voltages (in the hundreds of volts) and high currents (tens of amps) in order to function properly. Known drive circuitry for controlling piezoelectric fuel injectors is generally complicated and usually requires extensive energy.

[0007] It is an object of the present invention to provide an improved injector system and method for controlling fuel injection, which addresses the aforementioned problems.

[0008] According to a first aspect of the present invention there is provided an injector system for use in an internal combustion engine, the injector system including at least first and second injectors, and a drive circuit comprising select switch means for controlling independent selection of the first or second injector to permit a discharging current to be supplied to the selected injector during a discharging mode so as to initiate an injection event and charge/discharge switch means for controlling whether the discharging current is supplied to the selected injector or whether a charging current is supplied to the selected injector during a charging mode so as to terminate the injection event, wherein the first and second injectors are arranged electrically in parallel and operatively connected to the select switch means and the charge/discharge switch means so that activation of the charge/discharge switch means to terminate the injection event results in respective voltages across the first and second injectors tending to equalise.

[0009] It is a preferred embodiment for the injector system to include at least first and second injectors, each of which has a piezoelectric actuator. The invention is equally applicable, however, to systems in which the injectors have generally capacitive-like properties.

[0010] The advantage of arranging the injectors in parallel is that, at the end of the charging mode upon termination of the injection event by a selected injector, any voltage across the selected injector in excess of a predetermined voltage charge threshold tends to equalise with the voltage across the unselected injector(s). Thus, positive voltage ringing is damped due to excess energy being shared between the injectors. Accuracy of control of the injector and injector efficiency is therefore improved.

[0011] The injector system may, but need not, be manufactured to include voltage supply means for supplying charging and discharging voltages across the piezoelectric actuators.

[0012] In a preferred embodiment the drive circuit is configured as a half H-bridge circuit having a middle circuit branch, with the first and second injectors being arranged electrically in parallel with one another in the middle circuit branch.

[0013] Preferably, the charge/discharge switch means includes first and second charge/discharge switches, each of which permits unidirectional current flow when activated and prevents current flow when deactivated.

[0014] The select switch means preferably includes a first select switch for enabling the discharge current to flow through the first injector during the discharging mode thereof and a second select switch for enabling the discharge current to flow through the second injector during the discharging mode thereof.

[0015] The drive circuit of the system is preferably configured so that the discharging mode is achieved by activation (closing) of the second charge/discharge switch and activation (closing) of the select switch of the selected injector that is required to perform the injection event. The charging mode is conveniently achieved by activation of the first charge/discharge switch.

[0016] The drive circuit may also include voltage sensing means for monitoring the voltage across the selected injector (and also the unselected injector, if desired) and control means for receiving a signal indicative of the sensed voltage and providing a terminate control signal to the charge/discharge switch means to terminate the charging mode of the selected injector once a threshold charge voltage (V_{CHARGE}) is sensed. The control means may also be arranged to provide an initiate signal to the charge/discharge switch means to initiate the charging mode of the selected injector.

[0017] Preferably, the control means is arranged to control the select switch means so that the selected injector is de-selected following the end of the discharging mode, prior to a subsequent charging mode.

[0018] More preferably, therefore, the control means is arranged to control the select switch means so that the selected injector is re-selected at the start of the subsequent charging mode.

[0019] Alternatively, the control means is arranged to control the select switch means so that the selected injector is held selected at the end of the discharge mode and is held selected throughout (and preferably also following) the subsequent charging mode.

[0020] In a preferred embodiment the control means is arranged to control the select switch means so that both the first and second injectors are selected (that is, in a selected state) at the end of the charging mode and for a period thereafter, thereby to equalise the voltages across the injectors prior to a subsequent discharging mode, preferably equalising to a value just less than the threshold charge value. This provides the advantage that both injectors are at approximately the same voltage level before the subsequent discharging mode.

[0021] For this reason also the drive circuit may be configured to operate by providing a further additional control signal at engine start-up to equalise the voltages across each of the injectors to just less than the threshold charge voltage, and/or to provide the further additional control signal at engine shut-down.

[0022] The invention is applicable to a bank of at least two injectors, with each injector being arranged to inject fuel to an associated combustion space or engine cylinder. The bank may include any number of injectors, and an engine may have more than one injector bank depending on the number of engine cylinders.

[0023] In a particularly preferred embodiment of the invention, the injector system includes first and second injector banks, so that the drive circuit of the system controls operation of the first and second injector banks, the first injector bank including a first injector and a second injector and the second injector bank including a third injector and a fourth injector, the drive circuit including first select switch means associated with the first injector bank for controlling independent selection of the first or second injector to permit a discharging current to be supplied to the selected injector during a discharging mode so as to initiate an injection event, second select switch means associated with the second injector bank for controlling independent selection of the third or fourth injector to permit a discharging current to be supplied to the selected injector during a discharging mode so as to initiate an injection event, charge/discharge switch means for controlling whether the discharging current is supplied to the selected injector of either the first or the second injector bank or whether a charging current is supplied to said selected injector during a charging mode so as to terminate the injection event, and wherein the injectors of each bank are arranged electrically in parallel with the other injector (or injectors) of the same bank and operatively connected to the associated switch means and the charge/discharge switch means so that activation of the charge/discharge switch means to terminate the injection event results in respective voltages across injectors of the same bank tending to equalise.

[0024] Preferably, the charge/discharge switch means includes first and second charge/discharge switches for each bank, one being activated to initiating charging and one being activated to initiate discharging of a selected injector of the associated bank.

[0025] According to a second aspect of the invention there is provided a drive circuit for controlling the first and second injectors of the injector system set out in the accompanying claim set, wherein the drive circuit further includes at least first and second parallel current paths, each of which is provided with connection means connectable across a respective one of the first and second injectors of the system, in use, so that said injectors are arranged electrically in parallel with one another.

[0026] It will be appreciated, therefore, that another aspect of the invention is to provide an electrical drive circuit, which is not manufactured to include the injectors of the system with which it is used but which includes only electrical circuit components including the connection means for connection with the injectors, in use. The drive circuit of this aspect of the invention may include any of the preferred or optional features of the drive circuit aspect of the injector system described previously and set out in the accompanying claims.

[0027] According to a third aspect of the invention there is provided a control method for an injector system for use in an internal combustion engine, the injector system having at least first and second injectors and the method comprising controlling independent selection of the first or the second injector using select switch means to permit a discharging current to be supplied to the selected injector so as to initiate an injection event, controlling whether the charging current is supplied to the selected injector or whether a discharging current is supplied to the selected injector so as to terminate the injection event using charge/discharge switch means, arranging the first and second injectors electrically in parallel with one another and operatively connecting the injectors to the select switch means and the charge/discharge switch means, and activating the charge/discharge switch means so as to terminate the injection event and so that respective voltages across the first and second injectors at the end of the injection event tend to equalise.

[0028] It will be appreciated that the preferred and/or optional features of the first aspect of the invention are equally applicable to the second aspect of the invention, and may in particular provide preferred and/or optional method steps of the third aspect of the invention, alone or in appropriate combination.

[0029] For example, the method may include providing a first control signal to the select switch means to de-select the selected injector at the end of the discharging mode. The method may then include providing a further control signal to the select switch means to re-select the selected injector for the subsequent charging mode.

[0030] The method may alternatively include maintaining the selected injector in a selected state at the end of the discharging mode.

[0031] In a preferred embodiment, the method may include providing an additional control signal to the select switch means to ensure both the first and second injectors are selected at the end of the charging mode of either one, and for a period thereafter, thereby to equalise the voltages across the first and second injectors, prior to a subsequent injection event. This may be achieved by deselecting the first injector following the discharge mode and then reselecting the first injector at or just prior to the charging mode and, at substantially the same time, selecting the second injector at or just prior to the charging mode.

[0032] In a further preferred embodiment the method includes providing a further additional control signal to the select switch means to ensure both the first and second injectors are selected upon engine start-up and/or upon engine shut-down.

[0033] The invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 is a schematic diagram of a piezoelectric actuator of the type suitable for use in a fuel injector and including a stack of piezoelectric elements,

Figure 2 is a graph to illustrate a voltage waveform applied to a fuel injector to initiate an injection event, and

Figure 3 is a schematic diagram to illustrate an embodiment of an injector system of the present invention.

[0034] Referring to Figure 1, there is shown a piezoelectric actuator for a fuel injector of the negative-charge displacement type including a stack 10 of piezoelectric elements 12 (only two of which are numbered). The stack 10 is energisable and de-energisable to effect a change in length of the stack 10, and thereby to control movement of an injector valve needle towards and away from a valve needle seating so as to control injection. When in a contracted state (length x1), a positive, charging voltage is applied across the stack 10 to energise the stack. When in an extended state (length x2), a negative, discharging voltage is applied across the stack to de-energise the stack 10. It will be appreciated that in Figure 1 the degree to which the stack 10 extends and contracts is exaggerated.

[0035] Figure 2 shows a drive pulse 14, or voltage waveform, which is applied to the stack 10 to change between the contracted (x1) and extended (x2) states. The voltage waveform 14 varies between a charging voltage (V_{CHARGE}) and a discharging voltage ($V_{DISCHARGE}$). When the injector is in a non-injecting state, prior to injection, the voltage waveform 14 is at V_{CHARGE}, so that a relatively high voltage is applied to the piezoelectric stack 10. In this condition the stack 10 is in its extend state (length x2). Typically, V_{CHARGE} is around 200-300V. When it is required to initiate an injection event, the voltage waveform 14 is reduced to $V_{DISCHARGE}$, which, typically, is around -100V. This causes the piezoelectric stack 10 to contract (length x1), resulting in the inj ector valve needle lifting from its seating to initiate injection. To terminate injection, the voltage is increased to its charging voltage level, V_{CHARGE}, once again, thereby increasing the length of the stack (length x2) and thus causing the valve needle to re-seat.

[0036] Using known injector drive circuitry for piezoelectric fuel injectors of the aforementioned type it has been observed that, at the end of the charging phase at termination of injection, a degree of voltage ringing occurs as the voltage is caused to fluctuate about level V_{CHARGE}. The ringing effect is illustrated by the dashed line on Figure 2, and is prejudicial to the efficiency of operation of the injector and the accuracy of control, as described previously.

[0037] As shown in Figure 3, in a first embodiment of the present invention the injectors are arranged in 'banks' of two or more injectors, as illustrated by dashed lines and referenced at 21. Figure 3 therefore shows one injector bank 21 having three injectors 22a, 22b, 22c. This bank of injectors may be one of two identical injector banks (only one of which is shown in Figure 3) in a six cylinder engine, with each injector 22a, 22b, 22c of one bank delivering fuel to a different one of three engine cylinders and each injector of the other bank delivering fuel to a different one of three other engine cylinders. The arrangement and operation of the second injector bank is substantially identical to the first, and so only the first bank having injectors 22a, 22b, 22c will be described in detail. It will be appreciated by the skilled reader that further injector banks (each having two or more injectors) may be included in the system, depending on engine configuration and requirements.

[0038] The injectors 22a, 22b, 22c are of the negative-charge displacement type, as described previously. Generally, each individual injector is selected for injection under the control of a drive control circuit, referred to generally as 24, including select switch means operatively connected to the injectors 22a, 2b, 22c to permit independent control of each switch S1, S2, S3 thereof and charge/discharge switch means, Q1, Q2, which is operatively connected to the injectors 22a, 22b, 22c of a given bank so as to control injection by any one of them, depending on which is selected.

[0039] To inject with a selected injector, the select switch means S1, S2, S3 is operated so as to select the injector for injection. Energy is transferred to and from the piezoelectric stack so as to initiate and terminate injection by the selected injector using the charge/discharge switch means Q1, Q2. A control arrangement for controlling operation of the circuit 24 includes a microprocessor and memory of an Engine Control Module (ECM). The microprocessor and memory are configured to provide control signals for the select switches S1, S2, S3 and the charge/discharge switches Q1, Q2 so as to initiate a discharge operation (the discharge mode) in which the selected injector is opened. The microprocessor and the memory are also configured to provide control signals for the charge/discharge switch means Q1, Q2 so as to initiate a charging operation (the charging mode) in which the selected injector is closed, and may be configured to further provide control signals for the select switch means S1, S2, S3 during or following the charging mode, if necessary. The ways in which the microprocessor controls operation of the switch means S1, S2, S3, Q1, Q2 to control injection will be described in further detail below.

[0040] The drive circuit 24 employs a half H-bridge configuration and forms part of the ECM. The drive circuit 24 receives control signals from the ECM microprocessor and memory. A middle circuit branch of the half H-bridge serves as a bi-directional current path 26 and is provided with connection means in the form of positive and negative electrical connector terminals, at points x and y respectively, in each of three parallel current paths. Each injector is connected between the connection means (x, y) in a respective one of the parallel current paths, so that the injectors are arranged electrically in parallel. The middle circuit branch also includes an inductor 28, coupled in series with the parallel connection of the injectors 22a, 22b, 22c. Each injector has the electrical characteristics similar to those of a capacitor, with its piezoelectric actuator stack being chargeable to hold a voltage which is the potential difference between the charge (+) and discharge (-) terminals of the injector 22a, 22b, 22c. Charging and discharging of each injector 22a, 22b, 22c is achieved by controlling the current flow through the bi-directional current path 26 by means of the microprocessor.

[0041] The drive circuit 24 further includes a voltage input 30 for receiving a voltage V_S from a voltage source, such as vehicle battery voltage. The voltage V_S is increased to a higher step-up voltage, V_{C1}, via a step up transformer 32 (DC/DC converter). The step-up voltage, V_{C1}, is typically of the order of 200-300V and is applied to a first energy storage capacitor C1 via a first diode D1. The step-up transformer also applies voltage V_{C2} to a second energy storage capacitor C2 via a second diode D2. The step-up transformer has a return line coupled to the second diode D2. Typically, V_{C2} is of the order of 100V. As an alternative, other suitable electrical components may be used to provide a similar function to the step up transformer 32, if preferred.

[0042] The charge/discharge switch means of the drive circuit 24 includes first and second charge/discharge switches Q1 and Q2 respectively for controlling the charging and discharging operations of the injector. Each switch Q1, Q2 may take the form of an n-channel insulated gate bipolar transistor (IGBT) having a gate controlling current flow from the collector to the emitter. Each of the charge/discharge switches Q1, Q2 allows for unidirectional current flow from the collector to the emitter when turned on, and prevents current flow when turned off. Each switch Q1, Q2 has a respective recirculation diode D3, D4 connected across it to allow a recirculation current to return to the energy storage capacitors C1, C2 during an 'energy recovery' or 'recirculation' mode of operation of the circuit 24, as described in further detail below.

[0043] Each of the injectors 22a, 22b, 22c is connected in series with an associated select switch, S1, S2, S3 respectively, of the select switch means. Each of the first, second and third select switches S1, S2, S3 typically takes the form of an IGBT having a gate coupled to a gate drive which is powered at a bias supply input. When the select switch S1 associated with the first injector 22a, for example, is activated (or turned on) in conjunction with the charge/discharge switch Q2 being closed, current flow is permitted in a discharge direction through the selected injector. A diode D5 is connected in parallel with the select switch S1 to allow current flow in the charge direction during a charging mode of operation. Similarly, diodes D6 and D7 are connected in parallel with respective ones of the selects switches S2 and S3 for the second and third injectors.

[0044] A further diode D8 is provided between the bi-directional current path 26 on the injector side of the inductor 28 and the positive terminal of the first energy storage capacitor C1. Another diode D9 is provided between the negative terminal of the second energy storage capacitor C2 and the bi-directional current path 26 on the injector side of the inductor 28. The further diode D8 provides a 'voltage clamping effect' for a selected injector at the end of its charging mode, as it prevents the injector from being driven to voltages higher than V_{C1}. In certain circumstances the other diode D9 provides a recirculation path for current flow during a discharge mode of operation, as will be described in further detail later.

[0045] A current flow sensing and control means 38 may be connected within the bi-directional current path 26 to sense the current, compare the sensed current with predetermined first and second current thresholds, I_1 and I_2 respectively, and generate output signals accordingly. I_1 represents a peak current threshold and I_2 represents a recirculation current threshold. Both of the current threshold values, I_1 and I_2, are stored in the microprocessor and memory, along with a charge voltage threshold (V_{CHARGE}) and a discharge voltage threshold ($V_{DISCHARGE}$). If required, and preferably so, the current thresholds, I_1 and I_2, and the voltage thresholds, V_{CHARGE}, $V_{DISCHARGE}$, may be adjustable. A voltage sensing means (not shown) is also provided to sense the voltage, V_{SENSE}, across the injector that is selected for injection.

[0046] The control means of the circuit 24 includes control logic 34 for receiving the output of the current sensing and control means 38, the sensed voltage, V_{SENSE}, from the positive terminal (+) of the injectors 22a, 22b, 22c, and the various output signals provided from the microprocessor and memory. The control logic 34 may include software executed by the microprocessor and memory for processing the various inputs so as to generate control signals for each of the charge/discharge switches, Q1, Q2 and each of the injector select switches S1, S2 and S3.

[0047] The drive circuit 24 operates in a discharge phase or mode to open a selected one of the fuel injectors 22a, 22b, 22c, whereby the piezoelectric stack of the selected injector is contracted to cause the injector valve needle to lift from its seating. The drive circuit 24 also operates in a charge mode to close the fuel injectors 22a, 22b, 22c, whereby the piezoelectric stack of the selected injector is extended to cause the injector valve needle re-seat.

[0048] The discharge mode of operation of the system will now be described in further detail.

[0049] In order to operate in the discharge mode to open one of the injectors 22a, 22b, 22c of the bank, the second switch Q2 is activated (closed). Additionally, one of the injector select switches S1, S2, S3 is activated to select a desired one of the injectors 22a, 22b, 22c for injection. For example, if it is required to inject with the first injector 22a, the select switch S1 is closed. The other two injector select switches S2, S3 of the bank remain de-activated at this time as the second and third injectors 22b, 22c with which they are associated are not required to inject.

Upon activation of the second switch Q2, current is allowed to flow from the 100 V supply across capacitor C2, through the current sensing and control means 38, through the selected switch (S1 in this example), and into the corresponding negative side of the selected injector (22a in this example). A discharge current, $I_{DISCHARGE}$, flows from the injector load for injector 22a, through the inductor 28, through the closed switch Q2 and back to the negative terminal of capacitor C2. As the select switches S2 and S3 remain open, and due to the direction of their associated diodes, D6 and D7 respectively, substantially no current is able to flow through the second and third injectors 22b, 22c.

[0050] The current sensing and control means 38 monitors the current flow through the bi-directional path 26 as it builds up and, as soon as the peak current threshold I_1 is reached, an output signal is generated to initiate de-activation (opening) of the second switch Q2. At this point, the current that is built up in the inductor 28 recirculates through the diode D3 associated with the first (open) switch Q1. As a consequence, the direction of current flow through the inductor 28 and the selected one of the injectors 22a does not change. This is a "recirculation phase" of the discharging mode of operation of the drive circuit 24.

[0051] During the recirculation phase, current flows from the negative side of the 200 volt power supply across capacitor C1, through the current sensing and control means 38, through the selected switch S1, through the selected injector 22a, through the inductor 28, and finally through the diode D3 and into the positive side of capacitor C1. Thus, energy from the inductor 28 and the selected one of the injectors 22a is transferred to the capacitor C1 during the recirculation phase for energy storage purposes, the inductor 28 therefore providing a means of 'shaping' the current flow through the selected injector 22a. The current sensing and control means 38 monitors the recirculation current, so that when the recirculation current has fallen below the recirculation current threshold I_2, the comparator generates a signal to reactivate the second charge/discharge switch Q2 to continue the discharge operation.

[0052] By monitoring the voltage across the selected injector 22a using the voltage sensing means (not shown), the cycle of current build-up and recirculation continues until the appropriate discharge voltage level ($V_{DISCHARGE}$) across the selected injector has been achieved. In this discharge cycle, the capacitor C2 provides energy, while capacitor C1 receives energy for storage. Once the appropriate discharge voltage threshold $V_{DISCHARGE}$ is achieved, the half H-bridge circuit 24 is deactivated until a charge cycle is initiated.

[0053] At the end of the discharge mode, and approximately simultaneously with de-activation of the second switch Q2, the select switch S1 of the injector 22a is deactivated to open. Therefore, at the end of the discharge mode all three select switches S1, S2, S3 are deactivated (open).

[0054] In some circumstances it may be necessary to provide additional discharge pulses at the end of the discharge cycle through activation of the second switch Q2, so as to maintain the voltage across the injector at the discharge voltage threshold $V_{DISCHARGE}$. The means by which this can be achieved is the subject of the Applicant's co-pending European patent application, filed simultaneously with the present application.

[0055] In order to charge (close) the injector 22a, the first charge/discharge switch Q1 is activated to close allowing a charge current, I_{CHARGE}, to flow through the current path 26. This is referred to as charging mode of operation of the drive circuit. It is an essential step of the charging mode of operation that the first charge/discharge switch Q1 is activated to close. However, there are several ways in which the select switch means S1, S2, S3 may be operated during and following the charging mode, as described in further detail below.

[0056] A first charge mode of operation of the system will now be described in further detail.

[0057] The select switch S1 of the first injector 22a, which has previously been injecting, is activated to close again and a bi-directional current flows through the injector 22a during and following the charging mode. The second and third switches S2, S3 remain open. In such circumstances, the majority of the charge current I_{CHARGE} during the charging mode will flow through the previously discharged injector (i.e. the selected injector 22a in the example described), as this injector is at a much lower voltage level ($V_{DISCHARGE}$) at the start of the charging phase than the unselected injectors 22b, 22c (which are maintained, substantially, at voltage level V_{CHARGE}). The remaining injectors 22b, 22c that were not previously discharged will receive current if the corresponding voltages across them have dropped below the charge voltage threshold V_{CHARGE}. There is inevitably a small amount of current leakage through the diodes D6, D7 of the unselected injectors 22b, 22c during the discharging phase of the selected injector 22a, so that the voltage level on each of these injectors 22b, 22c will be slightly less than the nominal voltage level (V_{CHARGE}) in practice. Typically, for example, the unselected injectors 22b, 22c may discharge to a level around 199V, from 200V.

[0058] The current flow sensing and control means 38 monitors the current build-up and, as soon as the peak current threshold I_1 is reached, the control logic 34 generates a control signal to open the first switch Q1. At this point, the current that has built up in the inductor 28 recirculates through the diode D4 associated with the second (open) switch Q2. This is a recirculation phase of the charging mode of operation of the drive circuit 24. The direction of current flow through the inductor 28 and the injectors 22a, 22b, 22c does not change during the recirculation phase.

[0059] During this recirculation phase, current flows from the negative side of the 100 volt power supply across the capacitor C2, through the diode D4, through the inductor 28 and the injectors 22a, 22b, 22c, through the diodes D5, D6, D7, and the current sensing and control means 38 and into the positive side of energy storage capacitor C2. During this recirculation phase, energy from the inductor 28 and the piezoelectric injectors 22a, 22b, 22c is transferred to the energy storage capacitor C2. The current sense circuitry monitors the recirculation current and, when the recirculation current has fallen below the recirculation current threshold I_2, the comparator reactivates (closes) the first switch Q1 to continue the charge process. The voltage across the selected injector 22a is monitored and the cycle of current build-up and recirculation continues until the appropriate charge voltage level (threshold V_{CHARGE}) has been achieved. In this charging phase, the energy storage capacitor C1 provides energy and the energy storage capacitor C2 receives energy for storage. Once the appropriate charge voltage threshold, V_{CHARGE}, is achieved, the half H-bridge drive circuit 24 is deactivated until a subsequent discharge phase is initiated.

[0060] To summarise the previously described discharging mode of operation and the first mode of charging operation, when it is required to inject with a selected injector (e.g. the first injector 22a) of the first bank, the second switch Q2 is closed and the select switch S1 of the injector 22a is closed. During the discharge and recirculation (energy recovery) phases that follow, the second switch Q2 is automatically opened and closed until the voltage across the selected injector 22a is reduced to the appropriate voltage discharge level (i.e. $V_{DISCHARGE}$, as shown in Figure 2) to initiate injection. At the end of the discharge mode the select switch S1 is deactivated (opened). After a predetermined time for which injection is required, closing of the injector 22a is achieved by closing the first switch Q1, causing a charging current to flow through all three injectors 22a, 22b, 22c of the bank. During the subsequent charging and recirculation phases the first switch Q1 is continually opened and closed, until the appropriate charge voltage level is achieved (i.e. V_{CHARGE}, as shown in Figure 2). The select switch S1 of the previously discharged injector 22a is activated (closed again) at the start of the charging mode.

[0061] It is one benefit of arranging the injectors 22a, 22b, 22c of the bank in parallel, that any voltage overshoot, or positive voltage ringing, across the selected injector 22a, beyond the level V_{CHARGE}, at the end of the charging phase (i.e. at the end of an injection event) is 'shared' between the three injectors 22a, 22b, 22c. This arises due to the paralleling of the injectors allowing excess energy within the selected injector 22a, at the end of injection, to be distributed between the three injectors 22a, 22b, 22c equally. The effect of this is that positive voltage ringing for the selected injector 22a is damped. This would not be the case if the injectors 22a, 22b, 22c were not connected electrically in parallel.

[0062] The effect of damped positive voltage ringing is illustrated in Figure 2, by comparing the bold (damped) and dashed (undamped) lines at the end of the charging phase.

[0063] In order to inject with another one of the injectors of the bank, for example injector 22b or injector 22c, the select switch for the appropriate injector, S2 or S3, is activated and the charge/discharge switches Q1, Q2 are operated in a similar manner to that described previously. Again, a similar benefit is achieved at the end of injection by the second or third injector 22b, 22c due to the injectors of the bank being arranged in parallel.

[0064] A second alternative mode of operation of the select switches during a charging mode will now be described.

[0065] Instead of activating the select switch S1 to close at the start of the charging mode, the microprocessor may be programmed to hold the select switch S1 open during the charging mode, whilst the second and third select switches S2, S3 are also held open. In other words, all three switches S1, S2 and S3 are open for the charging mode. In such circumstances charging current flows through the injectors 22a, 22b, 22c by virtue of their respective diodes D5, D6, D7, as required. No damping of positive voltage ringing is achieved, however, as current is unable to flow to the negative side of the previously selected injector 22a with the switch S1 open. It is therefore preferable to use the first charging mode described previously, in which the select switch S1 of the previously selected in injector 22a is closed during the charging process.

[0066] A third alternative mode of operation of the select switches during a charging mode will now be described.

[0067] The microprocessor may be programmed so as to maintain the injector select switch S1 (of the previously selected injector 22a) closed for a period after which the charge voltage threshold, V_{CHARGE}, has been reached and also to activate the second and third select switches S2, S3 to close during this period. If the select switch has already been closed at the start of the charging phase then only the second and third switches S2, S3 need be activated to achieve this status, otherwise all three select switches S1, S2, S3 will need to be activated simultaneously.

[0068] By making sure all three switches S1, S2, S3 are closed following the end of the charging mode, the effects of positive and negative voltage ringing can be reduced. This is shown in Figure 2 by comparing the bold (damped) and dashed (undamped) lines. In such circumstances, with all three switches closed, the voltages across the three injectors 22a, 22b, 22c tend to equalise, although in practice this method results in each injector 22a, 22b, 22c being at a voltage level slightly less than the nominal charging voltage threshold, V_{CHRAGE}. This step may be performed as part of an engine start-up routine, so as to be sure all of the injectors have the same high (positive) voltage across them before injection is initiated with a discharging phase of the selected injector. The step may also be performed at engine shut-down.

[0069] It will be appreciated that the reference in the previous paragraph to the switches S1, S2, S3 being closed following the end of the charging phase can be achieved by actively selecting a previously unselected switch at the end of or just following the charging mode, or as a result of a selected switch having been held selected at the end of the discharging mode.

[0070] The microprocessor may use pre-calibrated data to determine the appropriate time period for which the injector select switches S1, S2, S3 should be closed after the voltage charge threshold is detected.

[0071] Referring once again to the general drive circuit configuration shown in Figure 3, the injectors 22a, 22b, 22c are in close proximity to their respective select switches S1, S2, S3. It will be appreciated, however, that in practice it may be desirable for the injectors 22a, 22b, 22c to be mounted remotely from the drive circuit 24, with injector connections at x and y to the drive circuit 24 through appropriate connecting leads.

[0072] In an alternative embodiment to that shown in Figure 3, the positions of each injector 22a, 22b, 22c and its corresponding select switch S1, S2, S3 may be interchanged. The embodiment of Figure 3, however, provides the advantage that shorting of the voltage-high side of the circuit is prevented in the event that the injector connecting leads short to ground.

[0073] It has been mentioned previously that it may be beneficial to provide extra discharge pulses at the end of the discharge phase. In this mode of operation, for example, any tendency of the voltage across the selected injector 22a to drift positive is counteracted by pulsed switching of the discharge switch Q2.

[0074] Likewise, additional charging pulses may be provided at the end of the charging phase by pulsed switching of the first switch Q1 to counteract any tendency of the voltage across the previously selected injector 22a to drift negative at the end of the charging phase.

[0075] As an alternative to providing additional pulses, however, if the current threshold values I_1, I_2 are adjustable by means of the controller then the tendency of the voltage across the selected injector to drift positive can be counteracted by reducing the threshold values

I_1, I_2 as the voltage across the selected injector 22a approaches the discharge voltage level, $V_{DISCHARGE}$.

[0076] In two of the aforementioned discharge modes of operation the select switch S1 of the injector 22a that is injecting is opened at the end of the discharge mode, approximately simultaneously with the discharge switch Q2 being deactivated (opened). In such modes of operation the provision of the diode D9 is important as it provides a recirculation path for residual energy in the inductor 28 at the end of the discharge mode to recirculate to the first energy storage capacitor VC1 via the diode D3 associated with the charge/discharge switch Q1.

[0077] If, as in a further alternative embodiment, the select switch S1 for the selected injector is not deactivated (opened) at the end of the discharge mode (i.e. it is maintained closed) then the requirement for the diode D9 is removed.

[0078] It will be appreciated that the invention is equally applicable to other injector arrangements comprising at least two injectors. For a two cylinder engine, for example, only a single bank of two injectors may be used. If two or more banks of injectors are employed, it will be appreciated that each is provided with its own select (S1, S2....Sn) switch means, and may be provided with its own charge/discharge (Q1, Q2) switch means, both of which are operable under the control of a common ECM microprocessor. Also, whilst the invention has been described specifically with reference piezoelectrically actuated fuel injectors, it is equally applicable to injectors systems in which the injectors having generally capacitive-like properties, such as motor-driven injectors.

Claims

1. An injector system for an internal combustion engine, the injector system comprising:

   at least a first and a second injector (22a, 22b), and

   a drive circuit (24) comprising select switch means (S1, S2) for controlling independent selection of the first or second injector (22a, 22b) to permit a discharging current to be supplied to the selected injector during a discharging mode so as to initiate an injection event,

   charge/discharge switch means (Q1, Q2) for controlling whether the discharging current is supplied to the selected injector (22a, 22b) or whether a charging current is supplied to the selected injector during a charging mode so as to terminate the injection event,

   wherein the first and second injectors (22a, 22b) are arranged electrically in parallel and operatively connected to the select and charge/discharge switch means (S1, S2, Q1, Q2) so that activation of the charge/discharge switch means to terminate the injection event results in respective voltages across the first and second injectors tending to equalise.

2. The injector system as claimed in claim 1, wherein each injector includes a piezoelectric actuator (10).

3. The injector system as claimed in claim 1 or claim 2, wherein the drive circuit (24) is configured as a half H-bridge circuit having a middle circuit branch (26), with the first and second injectors (22a, 22b) being arranged electrically in parallel with one another in the middle circuit branch.

4. The injector system as claimed in any one of claims 1 to 3, wherein the charge/discharge switch means includes first and second switches (Q1, Q2), each of which permits unidirectional current flow when activated and prevents current flow when deactivated.

5. The injector system as claimed in any one of claims 1 to 4, wherein the select switch means includes a first select switch (S1) for enabling discharging of the first injector (22a) during the discharging mode and a second select switch (S2) for enabling discharging of the second injector (22b) during the discharging mode.

6. The injector system as claimed in claim 5, wherein the discharging mode is achieved by activation of the second switch (Q2) and activation of the select switch of the injector selected to perform the injection event.

7. The injector system as claimed in claim 5 or claim 6, wherein the charging mode is achieved by activation of the first switch (Q1).

8. The injector system as claimed in any one of claims 1 to 7, including voltage sensing means for monitoring the voltage across the selected injector and control means (34) for receiving a signal indicative of the sensed voltage and providing a terminate control signal to the charge/discharge switch means (Q1, Q2) to terminate the charging mode once a threshold voltage (V_{CHARGE}) is sensed.

9. The injector system as claimed in claim 8, wherein the control means (34) is a microprocessor forming part of an engine control module.

10. The injector system as claimed in claim 8 or claim 9, wherein the control means (34) is arranged to control the select switch means (S1, S2) so that the selected injector is de-selected following the end of

the discharging mode, prior to a subsequent charging mode.

11. The injector system as claimed in claim 10, wherein the control means (34) is arranged to control the select switch means (S1, S2) so that the selected injector is re-selected for the charging mode.

12. The injector system as claimed in claim 8 or claim 9, wherein the control means (34) is arranged to control the select switch means (S1, S2) so that the selected injector is held selected at the end of the discharge mode.

13. The injector system as claimed in claim 11 or claim 12, wherein the control means (34) is arranged to control the select switch means (S1, S2, S3) so that both the first and second injectors (22a, 22b) are selected for a period at the end of the charging mode, thereby to equalise said voltages across the injectors (22a, 22b) prior to a subsequent discharging mode.

14. The injector system as claimed in any one of claims 1 to 13, wherein at least one of the select switch means (S1, S2, S3) and the charge/discharge switch means (Q1, Q2) comprises an n-channel insulated gate bipolar transistor.

15. A drive circuit (24) for use in the injector system as claimed in any one of claims 1 to 14, the drive circuit including the select switch means (S1, S2, S3), the charge/discharge switch means (Q1, Q2) and at least first and second parallel current paths, each of which is provided with connection means (x, y) connectable across a respective one of the first and second injectors of the system, in use, so that said injectors are arranged electrically in parallel with one another.

16. A method for controlling an injector system having at least first and second injectors (22a, 22b), the method comprising;
controlling independent selection of the first or the second injector (22a, 22b) using select switch means (S1, S2) to permit a discharging current to be supplied to the selected injector during a discharge mode so as to initiate an injection event,
controlling whether the charging or the discharging current is supplied to the selected injector or whether a charging current is supplied to the selected injector during a charging mode so as to terminate the injection event, using charge/discharge switch means (Q1, Q2),
arranging the first and second injectors (22a, 22b) electrically in parallel with one another and operatively connecting the injectors (22a, 22b) to the select and charge/discharge switch means, and
activating the charge/discharge switch means (Q1, Q2) so as to terminate the injection event and so that respective voltages across the first and second injectors at the end of the injection event tend to equalise.

17. The method as claimed in claim 16, wherein each injector includes a piezoelectric actuator (10).

18. The method as claimed in claim 16 or claim 17, including providing a first control signal to the select switch means (S1, S2) to de-select the selected injector (22a) at the end of the discharging mode.

19. The method as claimed in claim 18, including providing a first control signal to the select switch means (S1, S2) to select the selected injector (22a) for the charging mode.

20. The method as claimed in claim 16 or claim 17, including maintaining the selected injector (22a) in a selected state at the end of the discharging mode.

21. The method as claimed in claim 19 or claim 20, including providing an additional control signal to the select switch means (S1, S2, S3) to ensure both the first and second injectors (22a, 22b) are selected for a period at the end of the charging mode of either one, thereby to equalise the voltages across the first and second injectors (22a, 22b), prior to a subsequent injection event.

22. The method as claimed in any one of claims 16 to 21, including providing a further additional control signal to the select switch means (S1, S2, S3) to ensure both the first and second injectors (22a, 22b) are selected upon engine start-up and/or upon engine shut-down.

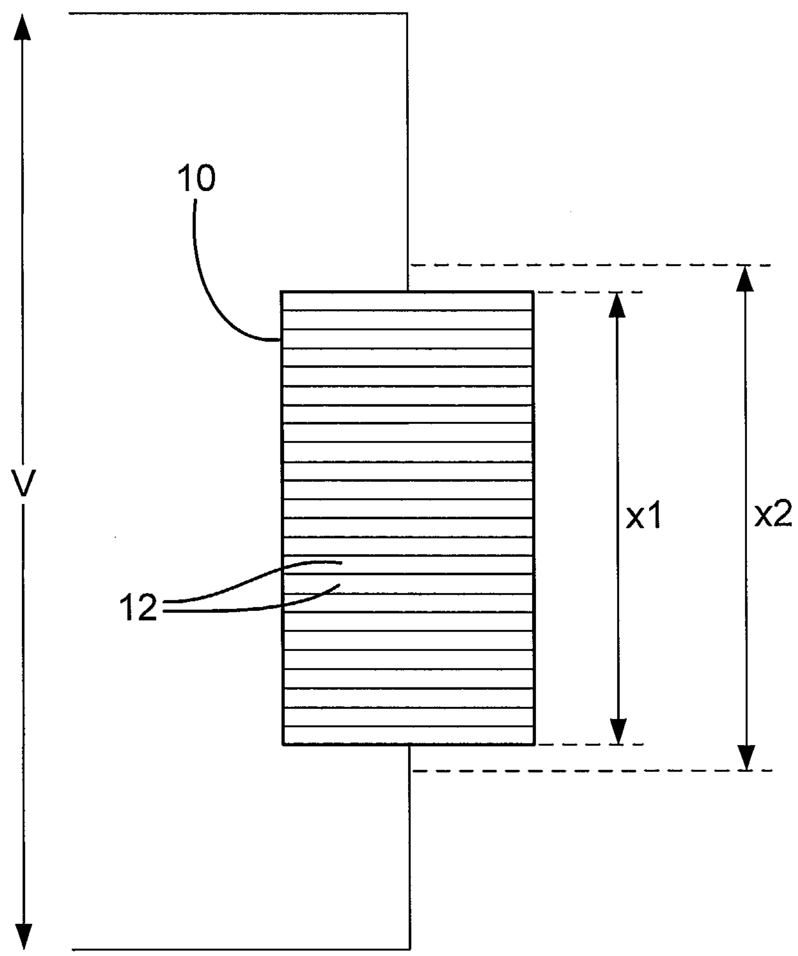

Fig. 1

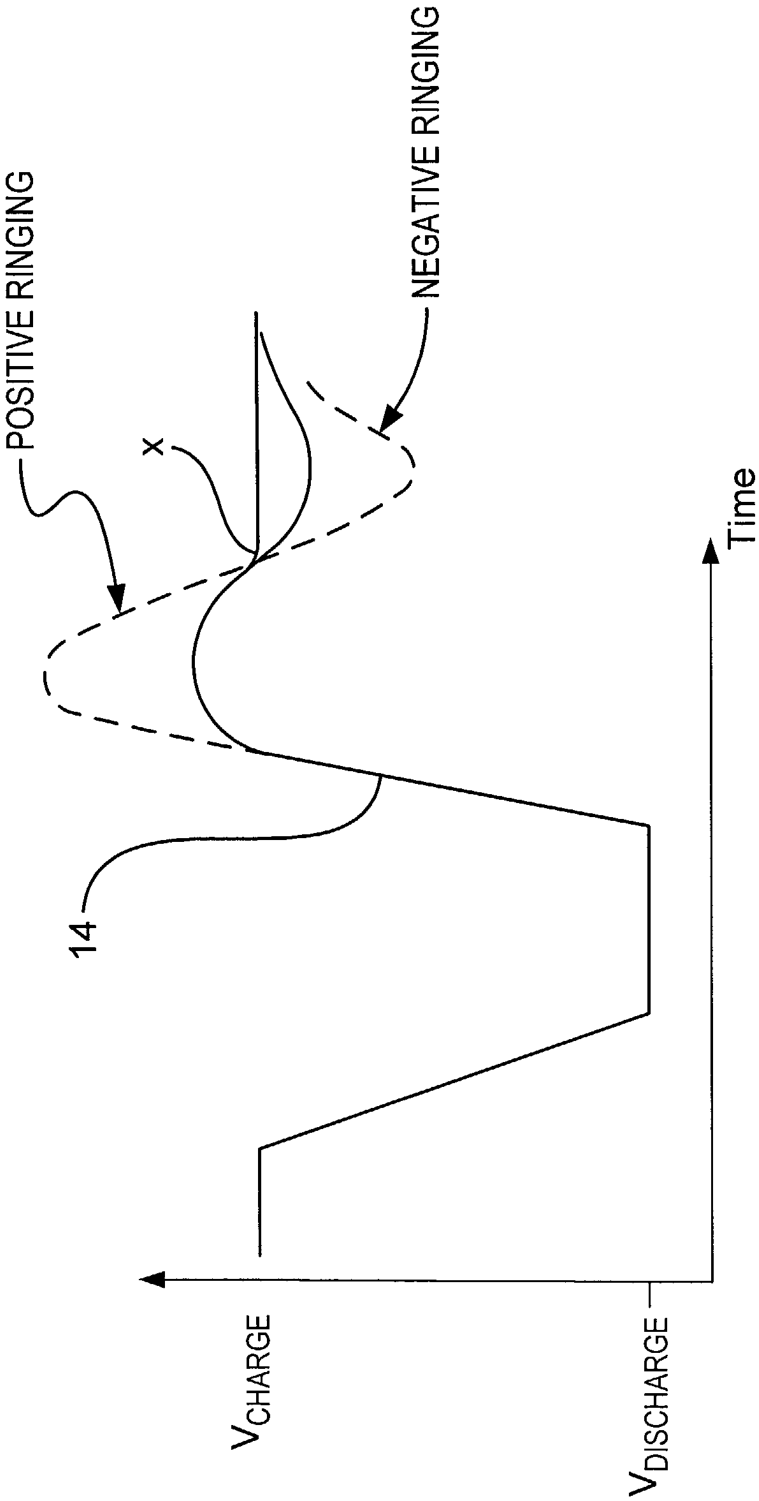
POSITIVE RINGING
NEGATIVE RINGING
x
14
Time
V_{CHARGE}
$V_{DISCHARGE}$

Fig.2

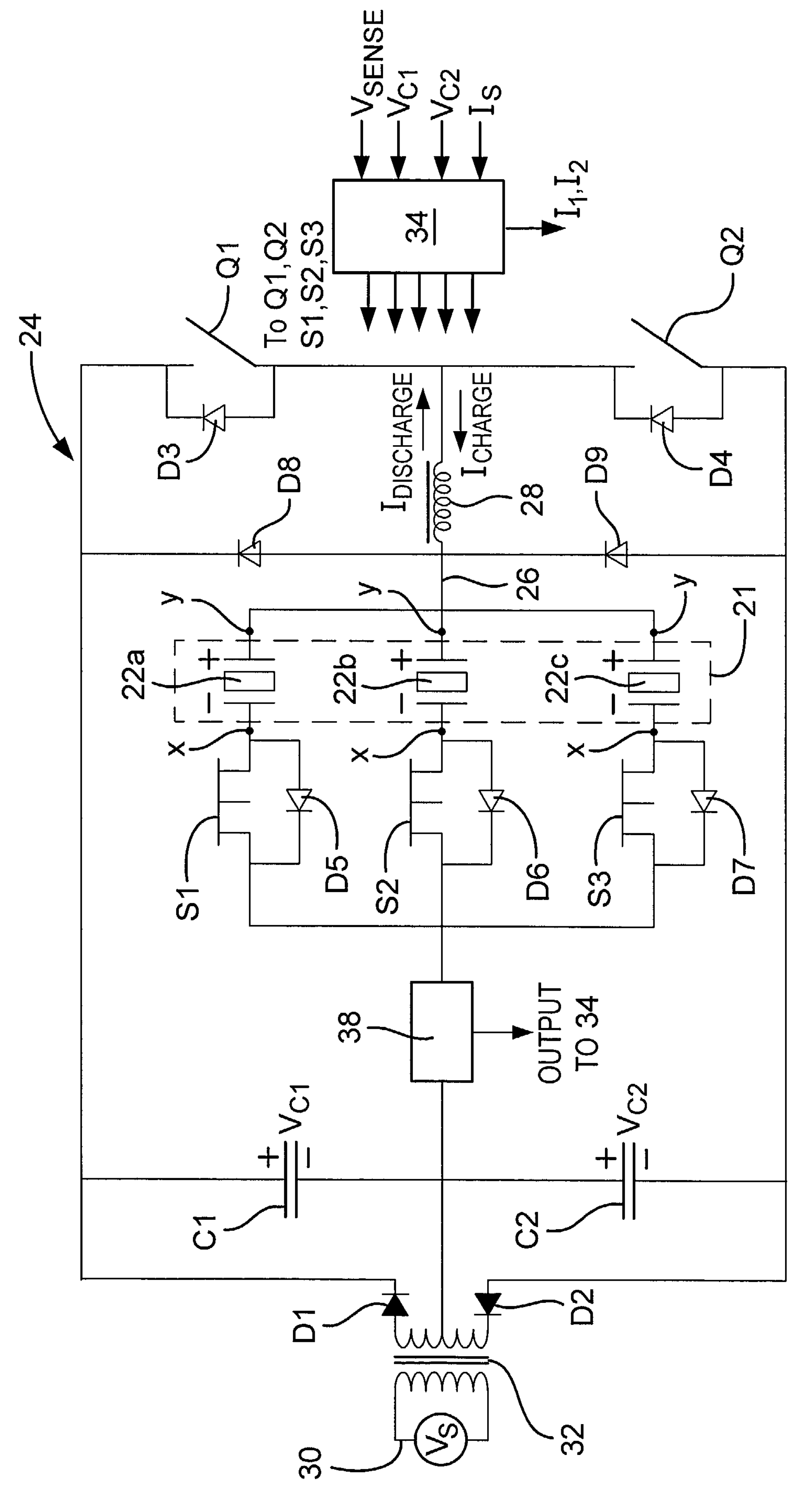
24
Q1
To Q1,Q2
S1,S2,S3
34
V_{SENSE}
V_{C1}
V_{C2}
I_S
I_1,I_2
Q2
D3
D8
$I_{DISCHARGE}$
I_{CHARGE}
28
D9
D4
26
y
y
y
21
22a
22b
22c
x
x
x
S1
D5
S2
D6
S3
D7
38
OUTPUT
TO 34
V_{C1}
V_{C2}
C1
C2
D1
D2
V_S
30
32

Fig.3