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(54) Method of operating a fuel injector

(57) A method of operating an injector drive circuit for an injector arrangement including at least one piezoelectric injector having an injector voltage, the injector drive circuit being operable to apply an activating voltage to the injector to initiate an injection event and a deactivating voltage to the injector to terminate an injection event. The method comprises i) activating injector select means to select a first injector for injection; ii) activating a first switch means to apply the activating voltage to the injector such that the injector voltage transitions from a first voltage level to a second voltage level; activating a second switch means to apply the deactivating voltage to the injector such that the injector voltage transitions from the second voltage level to the first voltage level; and, maintaining the activation state of the injector select means for a predetermined period of time after the injector transitions to the first voltage level. The invention has the advantage of reducing the voltage oscillation of the injector thus reducing noise emitted therefrom.

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Description

Technical Field

[0001] The invention relates to a method of operating a fuel injector. More specifically, the invention relates to a method of operating a piezoelectrically actuated fuel injector in order to decrease the level of noise generated by the injector.

Background to the Invention

[0002] In a direct injection internal combustion engine, a fuel injector is provided to deliver a charge of fuel to a combustion chamber, or cylinder, prior to ignition. Typically, the fuel injector is mounted in a cylinder head with respect to the combustion chamber such that its tip protrudes slightly into the chamber in order to deliver a charge of fuel thereto.

[0003] One type of fuel injector that is particularly suited for use in a direct injection engine is a so-called piezoelectric injector. Such an injector allows precise control of the timing and total delivery volume of a fuel injection event. This permits improved control over the combustion process which is beneficial in terms of exhaust emissions.

[0004] A known piezoelectric injector 2 and its associated control system 3 is shown schematically in Figure 1. The piezoelectric injector 2 includes a piezoelectric actuator 4 that is operable to control the position of an injector valve needle 6 relative to a valve needle seat 8. As known in the art, the piezoelectric actuator 4 includes a stack 7 of piezoelectric elements that expands and contacts in dependence on the voltage across the stack 7. The axial position, or 'lift', of the valve needle 6 is controlled by applying a variable voltage 'V' to the piezoelectric actuator 4. Although not shown in Figure 1, it should be appreciated that, in practice, the variable voltage would be applied to the actuator by connecting a power supply plug to the terminals of the injector.

[0005] By application of an appropriate voltage across the actuator, the valve needle 6 is caused either to disengage the valve seat 8, in which case fuel is delivered into an associated combustion chamber (not shown) through a set of nozzle outlets 10, or is caused to engage the valve seat 8, in which case fuel delivery through the outlets 10 is prevented.

[0006] For further background to the invention, an injector of this type is described in applicant's European Patent No. EP 0955901B. Such fuel injectors may be employed in compression-ignition (diesel) engines or spark ignition (petrol) engines.

[0007] Although piezoelectric injectors are adept at delivering precise quantities of fuel with accurate timing, they also have associated disadvantages. For example, during use, a piezoelectric injector emits vibrations due to the frequency of the drive voltage that is applied to the piezoelectric actuator. The vibrations travel down the injector, or through an injector positioning/clamping arrangement, and are transmitted to the engine. The engine accentuates certain frequencies such that at least a portion of the vibrations can be detected by the human ear.

[0008] At moderate and high engine speeds, the emitted noise of the injectors is drowned out by the combustion noise of the engine. However, at low engine speeds, particularly at engine idle and with the bonnet/hood raised, the audible injector noise is apparent. The detectable noise contributes to the overall noise/vibration/harshness (NVH) characteristics of the vehicle.

[0009] The optimisation of NVH characteristics is a significant factor in successful vehicle design since it influences the buying decision of the consumer. It is therefore desirable to reduce the amount of noise emitted by the injector in an effort to reduce the overall level of noise perceived by the user of the vehicle.

Summary of the Invention

[0010] Against this background, the invention provides a method of operating an injector drive circuit for an injector arrangement including at least one piezoelectric injector having an injector voltage, the injector drive circuit being operable to apply an activating voltage to the injector to initiate an injection event and a deactivating voltage to the injector to terminate an injection event. The method comprises activating injector select means to select a first injector for injection, activating a first switch means to apply the activating voltage to the injector such that the injector voltage transitions from a first voltage level to a second voltage level, activating a second switch means to apply the deactivating voltage to the injector such that the injector voltage transitions from the second voltage level to the first voltage level and, maintaining the activation state of the injector select means for a predetermined period of time after the injector transitions to the first voltage level.

[0011] The invention differs from known methods of operating piezoelectric fuel injectors in that the injector select means is kept in an activated state for an extended period of time. This is in contrast to known methods in which the injector select means is deactivated after the injector voltage has transitioned from the first voltage level to the second voltage level. The invention has the advantage of reducing the voltage oscillation of the injector thus reducing noise emitted therefrom.

[0012] The method of the invention is applicable to de-energise-to-inject injectors and also energise-to-inject injectors.

[0013] In order to control the rate at which the injector voltage transitions from the first voltage level to the second voltage level and vice-versa, it is preferred that the activation voltage and the deactivation voltage are applied in a pulse width modulated manner so as to result in a predetermined average current flow through the injector.

[0014] In an alternative embodiment of the invention, the method includes reactivating the first switch means after the injector voltage has transitioned from the second voltage level to the first voltage level, following which the first switch means is deactivated after a predetermined time period.

[0015] In this embodiment, advantageously, both positive and negative components of injector voltage oscillation are attenuated which improves the reduction of injector noise.

[0016] Although not essential to the invention, it is preferred that the first switch means and the injector select means are deactivated substantially at the same time. Preferably, the predetermined time period corresponds to a voltage oscillation time period of the injector.

[0017] In a further alternative embodiment, the injector arrangement comprises two or more injectors, and the method further includes activating a second injector select means after the injector voltage has transitioned from the second voltage level to the first voltage level.

[0018] Following activation, the second injector select means may be deactivated after a predetermined period. Preferably, the second injector select switch is deactivated substantially simultaneously with the first injector select switch.

[0019] In this embodiment, following the deactivation of the injector, current is permitted to cycle back and forth from injector to injector during the usual voltage oscillation period of the active injector. During this time, the injector voltage is clamped at the desired level and, due to the current flow between the injectors, energy is lost via the resistance of the injector drive circuit which damps the oscillatory displacement of the actuator within the injector.

[0020] It is also significant that as current is permitted to pass between the injectors, the effect is that the mechanical stiffness of the actuator is reduced. The result of this is to decrease the resonant frequency of the actuator such that, at high excitation frequencies, lower vibrational amplitudes are experienced, thus reducing the transmitted high frequency noise.

[0021] According to a second aspect of the invention there is provided a computer program product comprising at least one computer program software portion which, when executed in an executing environment, is operable to implement the method of the invention as described above.

[0022] In a third aspect of the invention there is provided a data storage medium having the or each computer software portion according to the second aspect of the invention

[0023] In a fourth aspect of the invention, there is provided a microcomputer provided with a data storage medium according to the third aspect of the invention.

[0024] It should be noted at this point that the terms 'close' and 'activate' are synonymous when used in connection with a switch and are intended to include the actuation of any suitable switching means to create an electrical connection across the switch. Similarly, the terms 'open' and 'deactivate' are synonymous in the context of a switch and are intended here to include the actuation of any suitable switching means to break an electrical connection across the switch.

<u>Brief Description of the Drawings</u>

[0025] Reference has already been made to Figure 1 which is a schematic representation of a known piezoelectric injector 2 and its associated control system. In order that it may be more readily understood, the invention will now be described with reference also to the following figures, in which:

Figure 2 is a circuit diagram of the injector drive circuit in Figure 1;

Figure 3 is a flow chart of a known method of operating the control circuit of Figure 2;

Figures 4a, 4b and 4c are state diagrams of charge select, discharge select and injector select switches according to the known control method of Figure 3;

Figures 4d and 4e are waveform profiles of voltage measured across the terminals of the injector and current flowing through current sensing means of the injector drive circuit of Figure 1, according the method of Figure 3;

Figure 5 is a flow chart of a method of operating the control circuit of Figure 2 according to a first embodiment of the invention;

Figures 6a, 6b and 6c are state diagrams of charge select, discharge select and injector select switches according to the method of Figure 5;

Figures 6d and 6e are waveform profiles of voltage measured across the injector terminals and current flowing through current sensing means of the injector drive circuit of Figure 1, according to the method of Figure 5;

Figure 7 is a flowchart of a method of operating the control circuit of Figure 2 according to a second embodiment of the invention;

Figures 8a, 8b and 8c are state diagrams of charge select, discharge select and injector select switches according to the method of Figure 7;

Figures 8d and 8e are waveform profiles of voltage measured between the injector terminals and current flowing through current sensing means of the injector drive circuit of Figure 1, according to the method of Figure 7;

Figure 9 is a flow chart of a method of operating the drive circuit of Figure 2 according to a third embodiment of the invention;

Figures 10a, 10b, 10c and 10d are state diagrams of charge select, discharge select and injector select switches according to the method of Figure 9; and

Figures 10e and 10f are waveform profiles of voltage measured between the injector terminals and current flowing through current sensing means of the injector drive circuit of Figure 1, according to the method of Figure 9.

Detailed Description of the Preferred Embodiments

[0026] Referring again to Figure 1, the piezoelectric injector 2 is controlled by an injector control unit 20 (hereinafter 'ICU') that forms an integral part of an engine control unit 22 (ECU). The ECU 22 monitors a plurality of engine parameters 24 and calculates an engine power requirement signal (not shown) which is input to the ICU 20. In turn, the ICU 20 calculates a required injection event sequence to provide the required power for the engine and operates an injector drive circuit 26 accordingly. The injector drive circuit is also shown as integral to the ECU 22, although it should be appreciated that this is not essential to the invention.

[0027] In order to initiate an injection, the injector drive circuit 26 causes the differential voltage between the high and low voltage terminals of the injector, V_1 and V_2, to transition from a high voltage (typically 200 V) at which no fuel delivery occurs, to a relatively low voltage (typically -55 V), which reduces the actuator voltage and therefore initiates fuel delivery. An injector responsive to this drive waveform is referred to as a 'de-energise to inject' injector and is operable to deliver one or more injections of fuel within a single injection event. For example, the injection event may include one or more so-called 'pre-' or 'pilot' injections, a main injection, and one or more 'post' injections. In general, several such injections within a single injection event are preferred to increase combustion efficiency of the engine.

[0028] Referring also to Figure 2, the drive circuit 26 includes an injector charge/discharge switching circuit 30 (hereinafter 'switching circuit') that is connected to an injector bank circuit 32 so as to control the voltage applied to a high side voltage input V and a low side voltage input V2 of the bank circuit 32.

[0029] The injector bank circuit 32 includes first and second branches 40, 42 both of which are connected in parallel between the high and low side voltage inputs V1 and V2. Each branch 40, 42 includes a respective injector INJ1, INJ2 and injector select switch QS1, QS2 by which means either one of the injectors can be selected for operation, as will be described later. It should be mentioned at this point that the piezoelectric actuator 4 of each injector 2 is considered electrically equivalent to a capacitor, the voltage difference between V1 and V2 determining the amount of electrical charge stored by the actuator and, thus, the position of the injector valve needle 8.

[0030] The switching circuit 30 includes three input voltage rails: a high voltage rail V_{HI} (typically 255 V) a mid voltage rail V_{MID} (typically 55 V) and a ground connection GND. The switching circuit 30 is operable to connect the high side voltage input V1 of the injector bank circuit to either the high voltage rail V_{HI} or the ground connection GND by means of first and second switches Q1, Q2 to which the injector bank 32 is connected, through an inductor L.

[0031] The switching circuit 30 is also provided with a diode D1 that connects the high side voltage input V1 of the bank circuit 32 to the high voltage rail V_{HI}. The diode D1 is oriented to permit current to flow from the high side input V1 of the bank circuit 32 to the high voltage rail V_{HI} but to prevent current flow from the high voltage rail V_{HI} to the high side voltage input V1 of the bank circuit 32.

[0032] The first switch Q1, when activated, connects the high side input V1 of the selected injector to the ground connection GND via the inductor L. Therefore, charge from the injector is permitted to flow from the selected injector, through the inductor L and switch Q1 to the ground connection GND, thereby serving to discharge the selected injector during an injector discharge phase. Hereinafter, the first switch will therefore be referred to as the 'discharge select switch' Q1. A diode D_{Q1} is connected across the second switch Q2 and is oriented to permit current to flow from the inductor L to the high voltage rail V_{HI} when the discharge select switch Q1 is deactivated, thus guarding against voltage peaks across the inductor L.

[0033] In contrast, the second switch Q2, when activated, connects the high side input V1 of the selected injector to the high voltage rail V_{HI} via the inductor L. In circumstances where the or each injector is discharged, activating the second switch Q2 causes charge to flow from the high voltage rail V_{HI}, through the second switch Q2 and the inductor L, and into the injector, during an injector charge phase, until an equilibrium voltage is reached (the voltage due to charge stored by the actuator equals the voltage difference between the high side and low side voltage inputs V1, V2). Hereinafter, the second switch will be referred to as the 'charge select switch' Q2. A diode D_{Q2} is connected across the discharge select switch Q1 and is oriented to permit current to flow from the ground connection GND through the inductor L to the high side input V1 when the charge select switch Q2 is deactivated, thus guarding against voltage peaks across the inductor L.

[0034] It should be appreciated that the inductor L constitutes a bidirectional current path since current flows in a first direction through the inductor L during the discharge phase and in a second, opposite direction during the injector charge phase.

[0035] The low side voltage input V2 of the injector bank circuit 32 is connected to the mid voltage rail V_{MID} via a voltage sense resistor 44. A current sensing and comparator means 50 (hereinafter 'comparator module') is connected in parallel with the sense resistor 44 and is operable to monitor the current flowing therethrough. In response to the current flowing through the resistor 44, the comparator module 50 outputs a control signal 52 (hereafter $Q_{CONTROL}$) that controls the activation status of the discharge select switch Q1 and the charge select switch Q2 so as to regulate the peak current flowing out of, or into, the operating injector. In effect, the comparator module 50 controls the activation status of the switches Q1 and Q2 to 'chop' the injector current between maximum and minimum current limits and achieve a predetermined average charge or discharge current. By this means, a high degree of control is afforded over the amount of electrical charge that is transferred off of the stack during a discharge phase and, conversely, onto the stack during a charge phase.

[0036] The operation of the injector drive circuit 26 during a typical discharge phase, followed by a charge phase, is described below with reference to Figure 3 and Figures 4a to 4e.

[0037] Initially, prior to time T_0, the injector drive circuit 26 is at equilibrium, that is to say both injectors INJ1 and INJ2 are fully charged such that no fuel injection is taking place. In these circumstances, the ICU 20 is in a wait state, indicated at step 100, awaiting an injection command signal from the ECU 22.

[0038] Following receipt of an injection command from the ECU 22 at step 102, the ICU 20 selects the injector that it is required to operate at step 104. For the purposes of this description, the selected injector is the first injector, INJ1. At substantially the same time, the ICU 20 initiates the discharge phase by enabling the discharge select switch Q1 so as to cause the injector INJ1 to discharge. A predetermined average discharge current through the injector is ensured by the operation of the comparator module 50 outputting the $Q_{CONTROL}$ signal between T_0 and T_1 to repeatedly deactivate and reactivate the discharge select switch Q1 such that the current remains within predetermined limits. It should be appreciated that the current flowing out of the injector INJ1 is therefore controlled in a pulse width modulated (PWM) manner.

[0039] The ICU 20 applies the predetermined average discharge current to the stack for a period of time (from T_0 to T_1) sufficient to transfer a predetermined amount of charge off of the stack (it should be appreciated that the discharge phase timings are read from a timing map by the ICU 20). At time T_1 (step 108), the ICU 20 deactivates the first injector select switch QS1 and disables the discharge select switch Q1, thus terminating the control signal $Q_{CONTROL}$, to prevent the injector discharging further. Thus during the time period T_0 to T_1 the stack voltage drops from a charged voltage level V_{CHARGE} to a discharged voltage level $V_{DISCHARGE}$, as indicated in Figure 4d.

[0040] At step 108, the ICU 20 maintains the injector INJ1 at the discharged voltage level $V_{DISCHARGE}$ for a predetermined dwell period, T_1 to T_2, such that the injector valve needle 8 is held open to perform an injection. At the end of the dwell period, at step 110, the ICU 20 enables the charge select switch Q2 in order to start the injector charge phase so as to terminate injection. As a result, the high side voltage input V1 of the injector bank circuit 32 is connected to the high voltage rail V_{HI} and charge begins to transfer into the injector INJ1.

[0041] As the current into the injector increases, the comparator module 50 monitors the current flowing through the sense resistor 44 and controls the activation status of the charge select switch Q2, via the control signal $Q_{CONTROL}$ to ensure a predetermined average charging current level. Between time T_2 and T_3, the ICU 20 applies the predetermined average charging current to the stack for a period of time sufficient to transfer a predetermined amount of charge onto the stack. At time T_3 (step 112), the ICU 20 disables the charge select switch Q2 and returns to the waiting step 100 ready for initiation of another injection event.

[0042] Although the above described method achieves an injection event adequately by discharging and then recharging the actuator, it has been observed that after the charge select switch Q2 has been disabled at time T_3 (step 112) the measured voltage across the injector fluctuates for a period of time, as indicated in Figure 4a as an 'oscillation period' Tp. During the oscillation period Tp, the forces applied to the stack, for example mechanical vibrations and pressure wave effects oscillate which causes a positive voltage oscillation followed by a negative voltage oscillation that eventually reduce in magnitude at which point the actuator displacement is at rest substantially at the target displacement.

[0043] Such oscillation is undesirable as it contributes to the overall noise envelope of the vehicle. An improved method of operating the injector drive circuit in order to reduce or substantially eliminate the oscillation period T_P is described below with reference to Figure 5 and Figures 6a to 6e.

Embodiment 1

[0044] Referring to Figure 5, at time T_0 the injector drive circuit 26 is in equilibrium such that both injectors INJ1 and INJ2 are fully charged. As a result, no fuel injection occurs and the ICU 20 is in a wait state, at step 200, awaiting an injection command signal from the ECU 22.

[0045] At step 202, the ICU 20 receives an injector command signal and, at step 204, selects the injector that is required to operate by activating the appropriate injector select switch, in this case the first injector select switch QS1 corresponding to the first injector INJ1 of the bank circuit 32. At substantially the same time, the ICU 20 enables the discharge select switch Q1 in order to initiate the discharge phase on INJ1. Charge therefore begins to flow from the injector INJ1, through the inductor

L and the discharge select switch Q1 to the ground connection GND.

[0046] As in Figures 4a to 4e, the ICU 20 applies a predetermined average discharge current for a predetermined time period (between time periods T_0 and T_1) sufficient to transfer a predetermined amount of charge off of the stack. As has been mentioned, during this time, the comparator module 50 is operable to monitor the current flow through the sense resistor 44 and repeatedly de-activate and activate the discharge select switch Q1 via the control signal $Q_{CONTROL}$. It should be appreciated that in this embodiment the injector INJ1 is controlled, initially, in a like manner to that described above with reference to Figure 3 and Figures 4a to 4e.

[0047] At time T_1 (step 206) the ICU 20 disables the discharge select switch Q1 such that the stack voltage resides at a discharged voltage level $V_{DISCHARGE}$. However, instead of deactivating the injector select switch QS1 at this point, the ICU 20 maintains the injector select switch QS1 in an activated state until after the injector INJ1 has been recharged, as is described below.

[0048] At step 208, the ICU 20 maintains the injector INJ1 at a discharged voltage level $V_{DISCHARGE}$ for a dwell period between time periods T_1 and T_2, such that the injector valve needle 8 is held open so as to perform an injection.

[0049] At the end of the dwell period, at step 210, the ICU 20 enables the charge select switch Q2 so as to start the injector charge phase and thus end injection by closing the injector valve needle 8. By activating Q2, the high side voltage input V1 of the injector bank circuit 32 is connected to the high voltage rail V_{HI} such that charge begins to transfer through the charge select switch Q2 and the inductor L, into the injector INJ1. As the current into the injector INJ1 increases, the comparator module 50 monitors the current through the sense resistor 44 and controls the activation status of the charge select switch Q2, via $Q2_{CONTROL}$, in a PWM manner so as to ensure a predetermined average charge current level. Between time T_2 and T_3, the ICU 20 applies the predetermined average charging current to the stack for a period of time sufficient to transfer a predetermined amount of charge onto the stack.

[0050] At time T_3 (step 212), the ICU 20 disables the charge select switch Q2. However, at this point, the injector select switch QS1 in still in an activated state, which has the effect of clamping the high side voltage input V1 of the bank circuit 32 to the high voltage rail V_{HI}. The benefit of this is that the voltage across the injector INJ1 does not overshoot or oscillate so the positive component of the voltage oscillation observed in Figure 3 is suppressed.

[0051] It can be seen on Figure 6e that since the positive component of voltage oscillation is prevented by clamping the voltage to V_{HI}, a relatively small discharge current flows out of the injector through the diode D1 to the high voltage rail V_{HI}. It will be noted that the voltage across the injector INJ1 is permitted to drop below the target charge voltage level V_{CHARGE} since the diode D1 prevents current from flowing to the injector INJ1 from V_{HI}. However, the displacement oscillation of the stack is significantly reduced in this embodiment, thus providing a reduction in the amount of audible noise generated by the injector.

[0052] The ICU 20 maintains the injector select switch QS1 in an activated state, at step 214, for a predetermined period T, shown on Figure 6d as between T_3 and T_4. Preferably the predetermined period T is calculated to the time period required for the voltage oscillation to have reduced, or damped, to an acceptable level. Alternatively, the length of the predetermined period T may be influenced by the requirement for a commanded injection event on the second injector INJ2 in the bank circuit 32.

[0053] Following deactivation of the injector select switch QS1, the ICU 20 returns to the wait state 200, ready to receive another injection command.

<u>Embodiment 2</u>

[0054] A further improved method of operating the injector drive circuit 26 is described below with reference to Figure 7 and Figures 8a to 8e.

[0055] In Figure 7, prior to time T_0, the injector drive circuit 26 is at equilibrium such that all injectors are fully charged and no fuel injection occurs. At this point, the ICU 20 is in a wait state, indicated at step 300, until it receives an injection command signal from the ECU 22.

[0056] At step 302, the ICU 20 receives an injector command signal and, at step 304, selects the injector to be operated, in this case the first injector INJI, by activating the appropriate injector select switch QS1. At substantially the same time, the ICU 20 enables the discharge select switch Q1 to initiate the discharge phase such that charge is transferred from the injector INJ1, through the inductor L and the discharge select switch Q1 to the ground connection GND.

[0057] As in the previous embodiment, between time periods T_0 and T_1, the comparator module 50 is operable to monitor the current flow through the sense resistor 44 and repeatedly de-activate and activate the discharge select switch Q1 via the control signal $Q_{CONTROL}$. As a result, during the discharge phase the ICU 20 applies the predetermined average discharge current to the stack for a period of time sufficient to transfer a predetermined amount of charge off of the stack.

[0058] At step 306, the ICU 20 deactivates the discharge select switch Q1. As in the previous embodiment of the invention, the ICU 20 maintains the injector select switch QS1 in an activated state until after the injector has been recharged.

[0059] At step 308, the ICU 20 maintains the injector INJ1 in a discharged state for a dwell period, between T_1 and T_2, during which time the injector valve needle 8 is held open to perform an injection.

[0060] At the end of the dwell period, at step 310, the

ICU 20 enables the charge select switch Q2 to initiate the injector charge phase and, thus, end the injection event by closing the injector valve needle 8. By activating Q2, the high side voltage input V1 of the injector bank circuit 32 is connected to the high voltage rail V_{HI} such that charge begins to transfer to the injector INJ1, though the charge select switch Q2 and the inductor L. As the current into the injector INJ1 increases, the comparator module 50 monitors the current and controls the activation status of the charge select switch Q2 via the control signal $Q_{CONTROL}$ so as to ensure a predetermined average charge current level. Between time T_2 and T_3, the ICU 20 applies the predetermined average charging current to the stack for a period of time sufficient to transfer a predetermined amount of charge onto the stack. At time T_3 (step 312), the ICU 20 disables the charge select switch Q2.

[0061] Up until this point, operation of the injector drive circuit 26 is substantially the same as in the previous embodiment. However, rather than deactivating the charge select switch Q2 at this point (as in the first embodiment of the invention), the ICU 20 maintains the activation state for a predetermined period T, as indicated in Figure 8a. In addition, it should be noted that the injector select switch QS1 is also in an activated state at this point.

[0062] After the predetermined time period T following the injector charge phase, between T_3 and T_4, the ICU 20 deactivates the charge select switch Q2 and the injector select switch QS1 substantially simultaneously.

[0063] As in the first embodiment, between T_3 and T_4 the high side voltage input terminal V1 is effectively clamped to the high voltage rail V_{HI} by means of the activated injector select switch QS1. Therefore, as the actuator displacement overshoots at the end of the charging phase, a relatively small amount of current will flow out of the injector to V_{HI}. However, this embodiment provides a means to further reduce the voltage oscillation by reducing the extent of the negative voltage component. Since the charge select switch Q2 remains activated after the charging phase, charge is permitted to flow from the high voltage rail V_{HI}, through the charge select switch Q2 and the inductor L, into the injector INJ1. It should be noted, however, that due to the impedance of the inductor L the current flow is less than the positive component of the oscillation and some voltage drop does occur. Nonetheless, the magnitude of the voltage oscillation is significantly reduced thus resulting in a beneficial reduction in injector noise.

<u>Embodiment 3</u>

[0064] A still further improved method of operating the injector drive circuit 26 is described below with reference to Figure 9 and Figures 10a to 10f.

[0065] In Figure 9, prior to time T_0 the injector drive circuit 26 is in equilibrium such that both injectors INJ1 and INJ2 are fully charged so no fuel injection occurs. At this point, the ICU 20 is in a wait state, indicated at step 400, until it receives an injection command signal from the ECU 22, at step 402.

[0066] At step 404, in response to the injection command signal, the ICU 20 activates the first injector select switch QS1 to select the first injector INJ1 for operation. At substantially the same time, the ICU 20 enables the discharge select switch Q1 to initiate the discharge phase such that charge is transferred from the injector INJ1 through the inductor L and the discharge select switch Q1 to the ground connection GND. As in previous embodiments, the ICU 20 applies a predetermined average discharge current for a predetermined period of time (from T_0 to T_1) sufficient to transfer a predetermined amount of charge off of the stack. As has been mentioned, during this time, the comparator module 50 is operable between time periods T_0 and T_1 to monitor the current flow through the sensor resistor 44 and repeatedly de-activate and activate the discharge select switch Q1 via the control signal $Q_{CONTROL}$.

[0067] At time T_1 (step 406) the ICU 20 disables the discharge select switch Q1 such that the stack voltage resides at a discharged voltage level $V_{DISCHARCE}$. As in the first embodiment, rather than deactivate the injector select switch QS1 at this point (i.e. when the injector INJ1 has been discharged) the ICU 20 maintains the injector select switch QS1 in an activated state for a predetermined period of time after the injector has been recharged, as is described below.

[0068] At step 408, the ICU 20 maintains the injector INJ1 at the discharged voltage level $V_{DISCHARGE}$ for a predetermined dwell period, between time periods T_1 and T_2, during which time the injector valve needle 8 is held open to perform an injection.

[0069] At the end of the dwell period, at step 410, the ICU 20 enables the charge select switch Q2 so as to initiate the injector charge phase and thus end the injection event. By activating Q2, the high side voltage input V1 of the injector bank circuit 32 is connected to the high voltage rail V_{HI} and charge begins to transfer through the charge select switch Q2 and the inductor L, and into the injector INJ1. As the current into the injector INJ1 increases, the comparator module 50 monitors the current and controls the activation status of the charge select switch Q2, via the control signal $Q_{CONTROL}$, in a PWM manner so as to ensure a predetermined average current level. Between T_2 and T_3, the ICU 20 applies the predetermined average charging current to the stack for a period of time sufficient to transfer a predetermined amount of charge onto the stack. At time T_3, the ICU 20 disables the charge select switch Q2.

[0070] At step 414, the ICU 20 activates the second injector select switch QS2 for a predetermined period of time T. After the predetermined time period T following the injector charge phase, between T_3 and T_4, the ICU 20 deactivates both injector select switches QS1, QS2 substantially simultaneously.

[0071] This embodiment provides the advantage that the overshoot and undershoot components of the injector voltage during the oscillation phase are substantially eliminated. As in the first embodiment of the invention, the high side voltage input V1 of the first injector INJ1 is clamped to the high voltage rail V_{HI}. However, since the injector select switch QS2 for the second injector INJ2 is activated, current is permitted to circulate through the resistive network of the injector bank 30 that connects the first and second injectors INJ1, INJ2. By permitting current to cycle between the injectors INJ1, INJ2 during the oscillation period, energy is dissipated through the circuit impedance of the injector bank circuit 32. The dissipation of actuator energy acts to damp the displacement of the actuator and this has the observed result of reducing the high frequency noise contribution from the injectors.

[0072] It is also significant that as current is permitted to pass to/from the actuators of the injectors, the mechanical stiffness of the actuators is reduced. This has the effect of decreasing the resonant frequency of the actuator such that, at high excitation frequencies, lower vibrational amplitudes are experienced, which is linked to a reduction in high frequency noise.

[0073] It should be appreciated that various modifications may be made to the embodiments described above without departing from the broad concept of the invention, as defined by the claims. For example, in circumstances where the drive circuit includes more injectors per bank, all injector select switches of the injector bank may be opened during the oscillation period. The benefit of this is to dissipate the energy flowing between the injectors more quickly.

[0074] Also it should be appreciated that although the ICU 20 has been described as integral to the ECU 22, this need not be the case and the ICU 20 may be arranged to be separated physically from the ECU 22.

Claims

1. A method of operating an injector drive circuit for an injector arrangement including at least one piezoelectric injector having an injector voltage, the injector drive circuit being operable to apply an activating voltage to the injector to initiate an injection event and a deactivating voltage to the injector to terminate an injection event, wherein the method comprises:

    activating injector select means (QS1, QS2) to select a first injector (INJ1, INJ2) for injection;
    activating a first switch means (Q1) to apply the activating voltage to the injector (INJ1) such that the injector voltage transitions from a first voltage level (V_{CHARGE}) to a second voltage level ($V_{DISCHARGE}$);
    activating a second switch means (Q2) to apply the deactivating voltage to the injector (INJ1) such that the injector voltage transitions from the second voltage level ($V_{DISCHARGE}$) to the first voltage level (V_{CHARGE}); and
    maintaining the activation state of the injector select means (QS1) for a predetermined period (T) after the injector transitions to the first voltage level (V_{CHARGE}).

2. The method of claim 1, wherein the step of applying the activating voltage to the injector includes applying the activating voltage in a pulse width modulated manner so as to achieve a predetermined average activation injector current.

3. The method of claim 1 or claim 2, wherein the step of applying the deactivating voltage to the injector includes applying the deactivating voltage in a pulse width modulated manner so as to achieve a predetermined average deactivation injector current.

4. The method of any one of claims 1 to 3, further including reactivating the first switch means (Q1) after the injector voltage has transitioned from the second voltage level ($V_{DISCHARGE}$) to the first voltage level (V_{CHARGE}).

5. The method of claim 4, wherein the first switch means (Q1) is deactivated a predetermined period (T) after its reactivation.

6. The method of claim 5, wherein the first switch means (Q1) and the injector select means (QS1) are deactivated substantially simultaneously.

7. The method of claim 5 or claim 6, wherein the predetermined period (T) is selected to be equal to a voltage oscillation period (T_P) of the injector.

8. The method of any one of claims 1 to 4, wherein the injector arrangement includes two or more injectors, the method further including activating a second injector select means (QS2) after the injector voltage has transitioned from the second voltage level ($V_{DISCHARGE}$) to the first voltage level (V_{CHARGE}).

9. The method of claim 8, wherein the second injector select means (QS2) is deactivated a predetermined period (T) after its activation.

10. The method of claim 9, wherein the first injector select means (QS1) and the second injector select means (QS2) are deactivated substantially simultaneously.

11. The method of claim 9 or claim 10, wherein the predetermined period (T) is selected to be equal to a voltage oscillation period (Tp) of the injector (INJ1).

12. The method of any one of claims 1 to 11, wherein

the injector is discharged to initiate an injection event.

13. A computer program product comprising at least one computer program software portion which, when executed in an executing environment, is operable to implement the method of any one of claims 1 to 12.

14. A data storage medium having the or each computer software portion of claim 13 stored thereon.

15. A microcomputer provided with the data storage medium of claim 14.

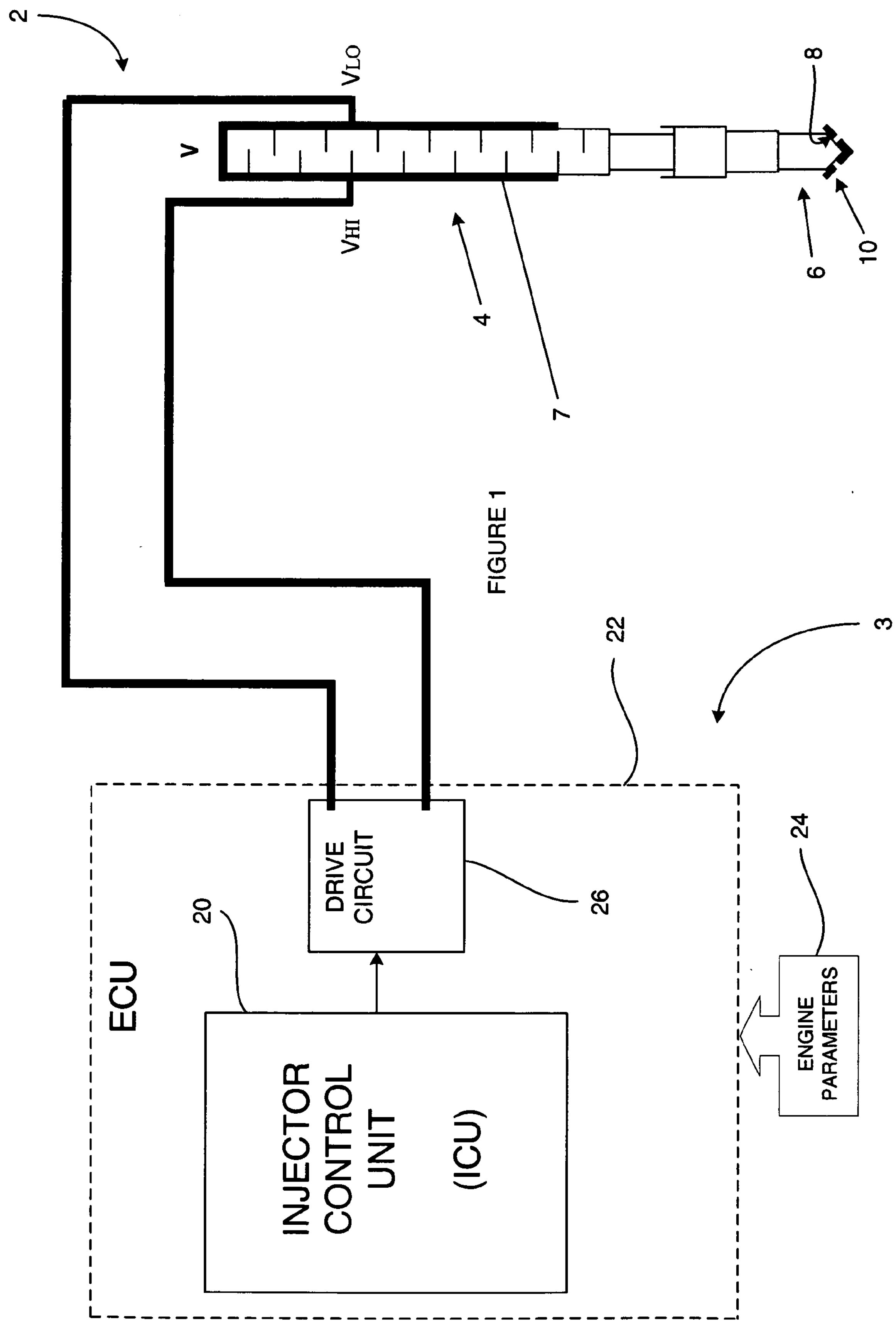

2
VLO
V
VHI
4
7
8
6
10
3
22
ECU
DRIVE CIRCUIT
26
20
INJECTOR CONTROL UNIT
(ICU)
24
ENGINE PARAMETERS

FIGURE 1

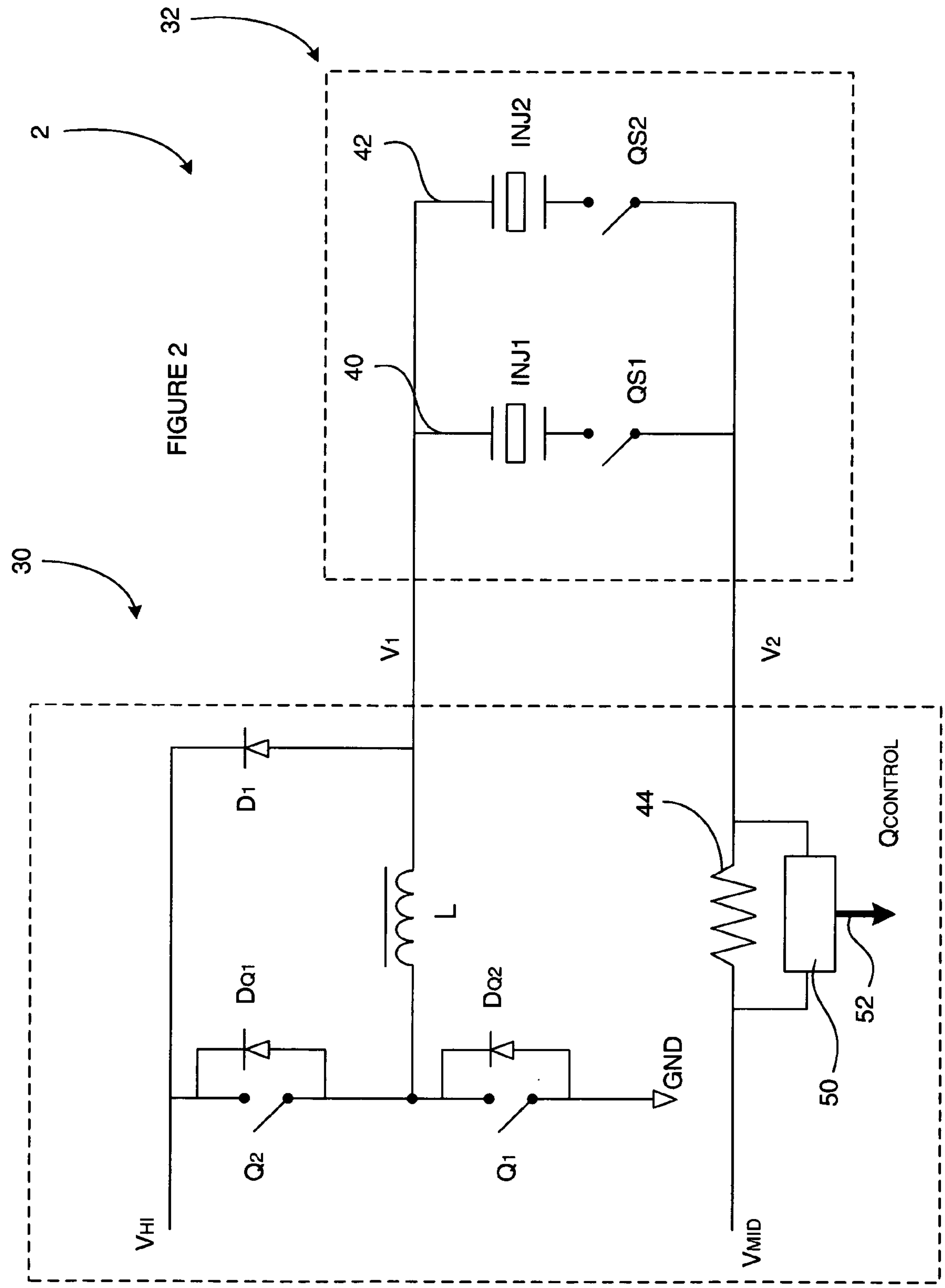

32
2
42
INJ2
QS2
40
INJ1
QS1
30
V1
V2
D1
L
DQ1
DQ2
44
QCONTROL
52
50
Q2
Q1
VGND
VHI
VMID

FIGURE 2

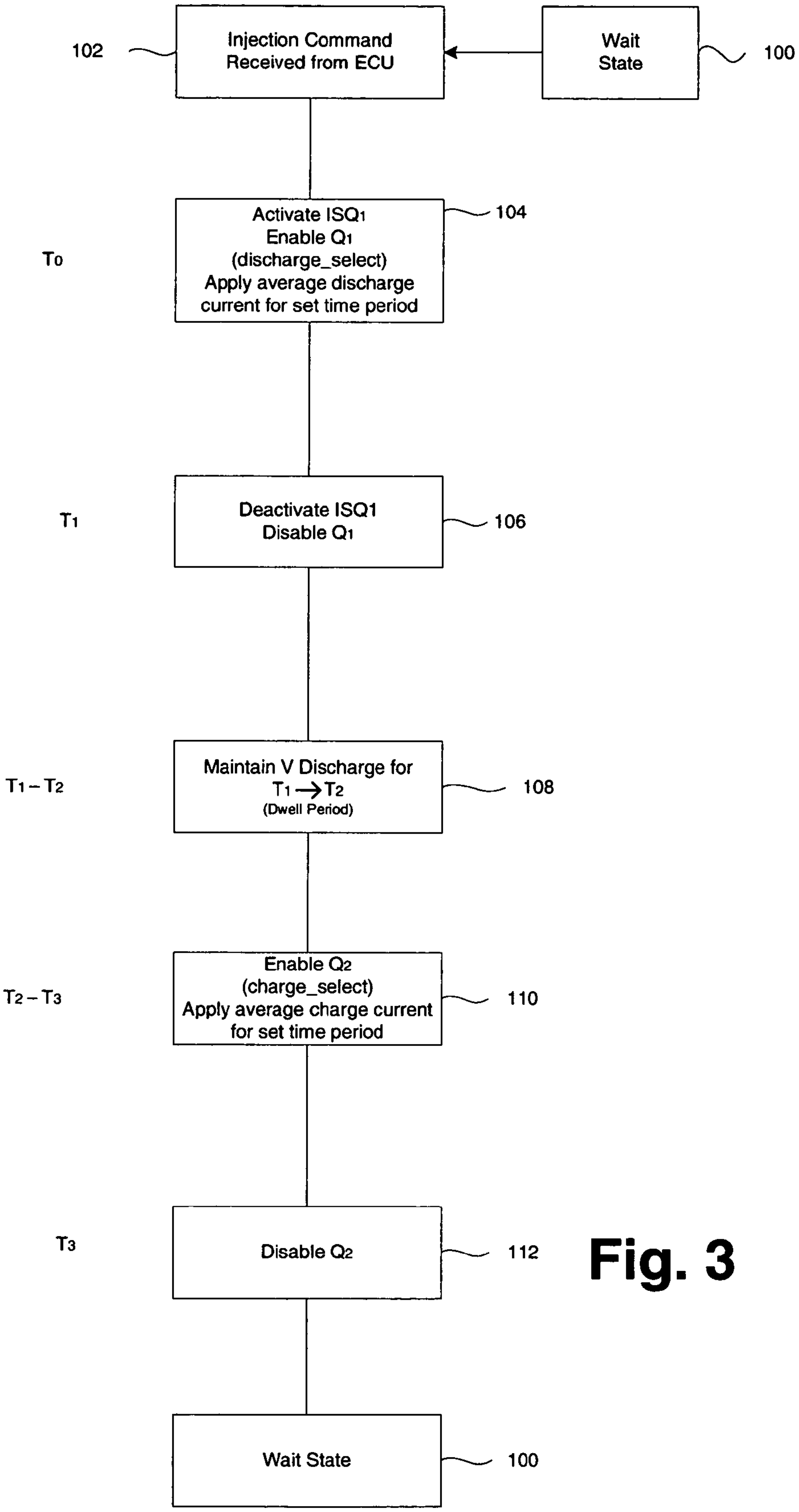

Wait
State
100
Injection Command
Received from ECU
102
T0
Activate ISQ1
Enable Q1
(discharge_select)
Apply average discharge
current for set time period
104
T1
Deactivate ISQ1
Disable Q1
106
T1 – T2
Maintain V Discharge for
T1 → T2
(Dwell Period)
108
T2 – T3
Enable Q2
(charge_select)
Apply average charge current
for set time period
110
T3
Disable Q2
112
Wait State
100

Fig. 3

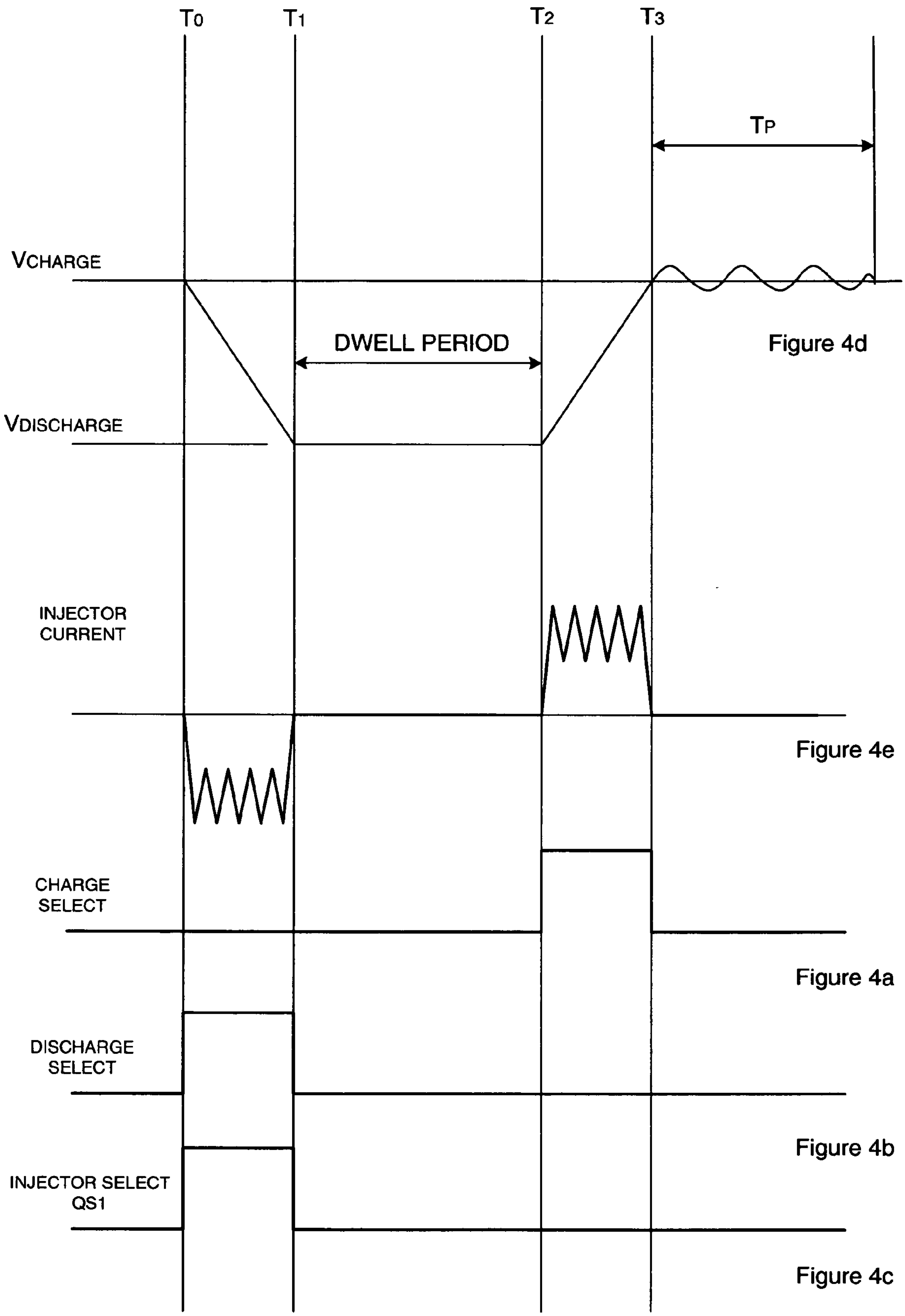


Figure 4d

Figure 4e

Figure 4a

Figure 4b

Figure 4c

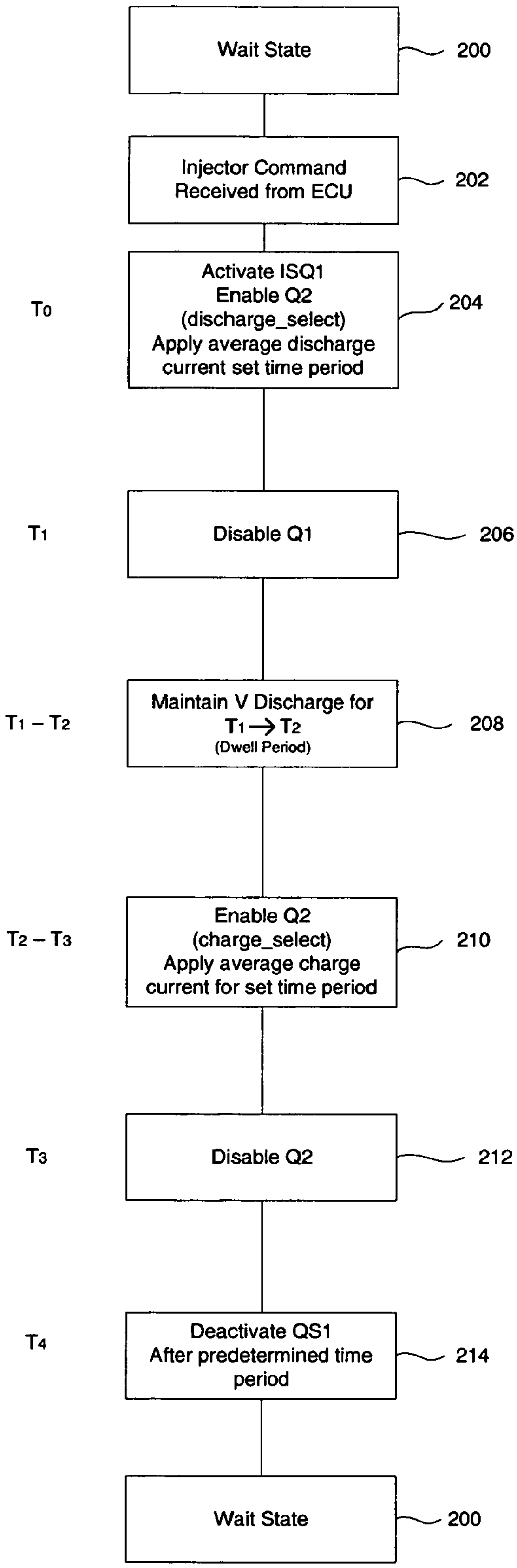
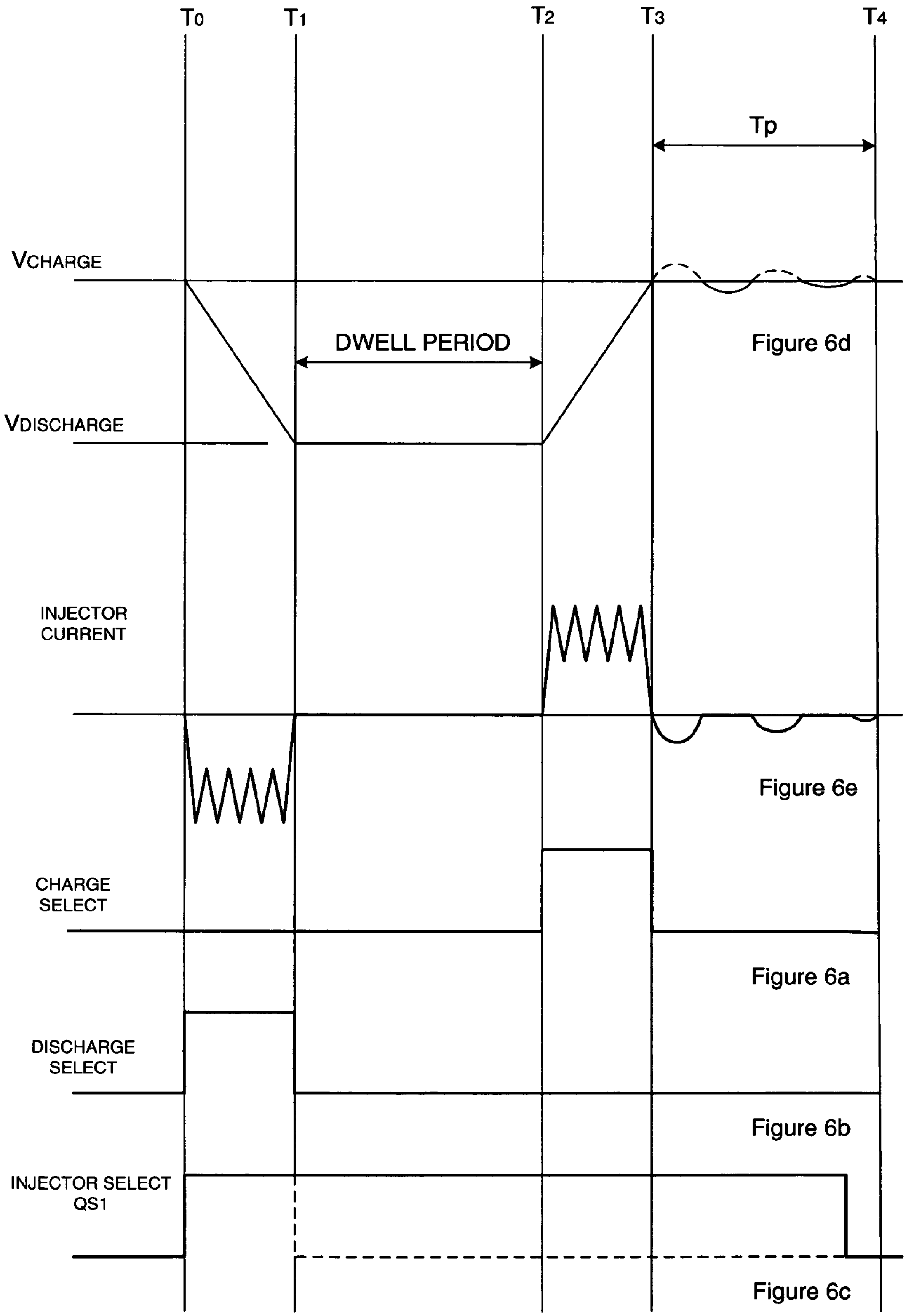

Wait State
200
Injector Command Received from ECU
202
T0
Activate ISQ1
Enable Q2
(discharge_select)
Apply average discharge current set time period
204
T1
Disable Q1
206
T1 – T2
Maintain V Discharge for T1 → T2
(Dwell Period)
208
T2 – T3
Enable Q2
(charge_select)
Apply average charge current for set time period
210
T3
Disable Q2
212
T4
Deactivate QS1
After predetermined time period
214
Wait State
200

Fig. 5


T0
T1
T2
T3
T4
Tp
VCHARGE
DWELL PERIOD
VDISCHARGE
Figure 6d
INJECTOR CURRENT
Figure 6e
CHARGE SELECT
Figure 6a
DISCHARGE SELECT
Figure 6b
INJECTOR SELECT QS1
Figure 6c

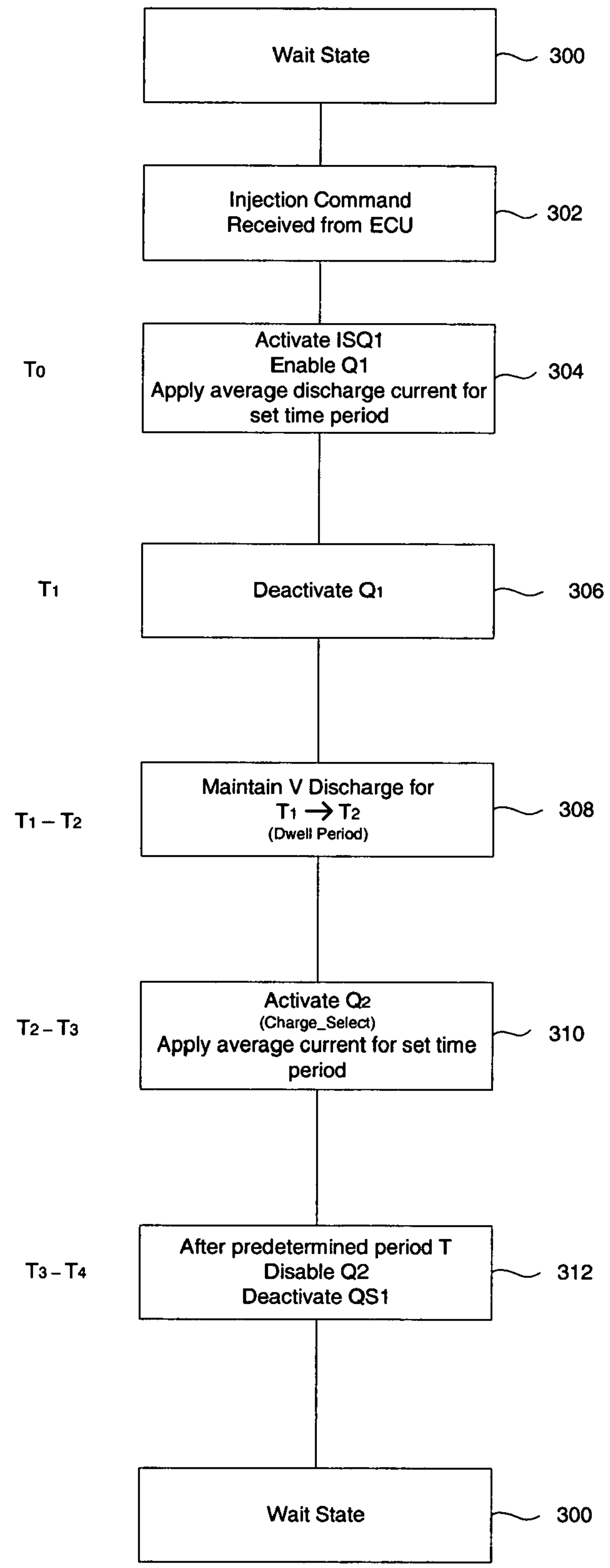
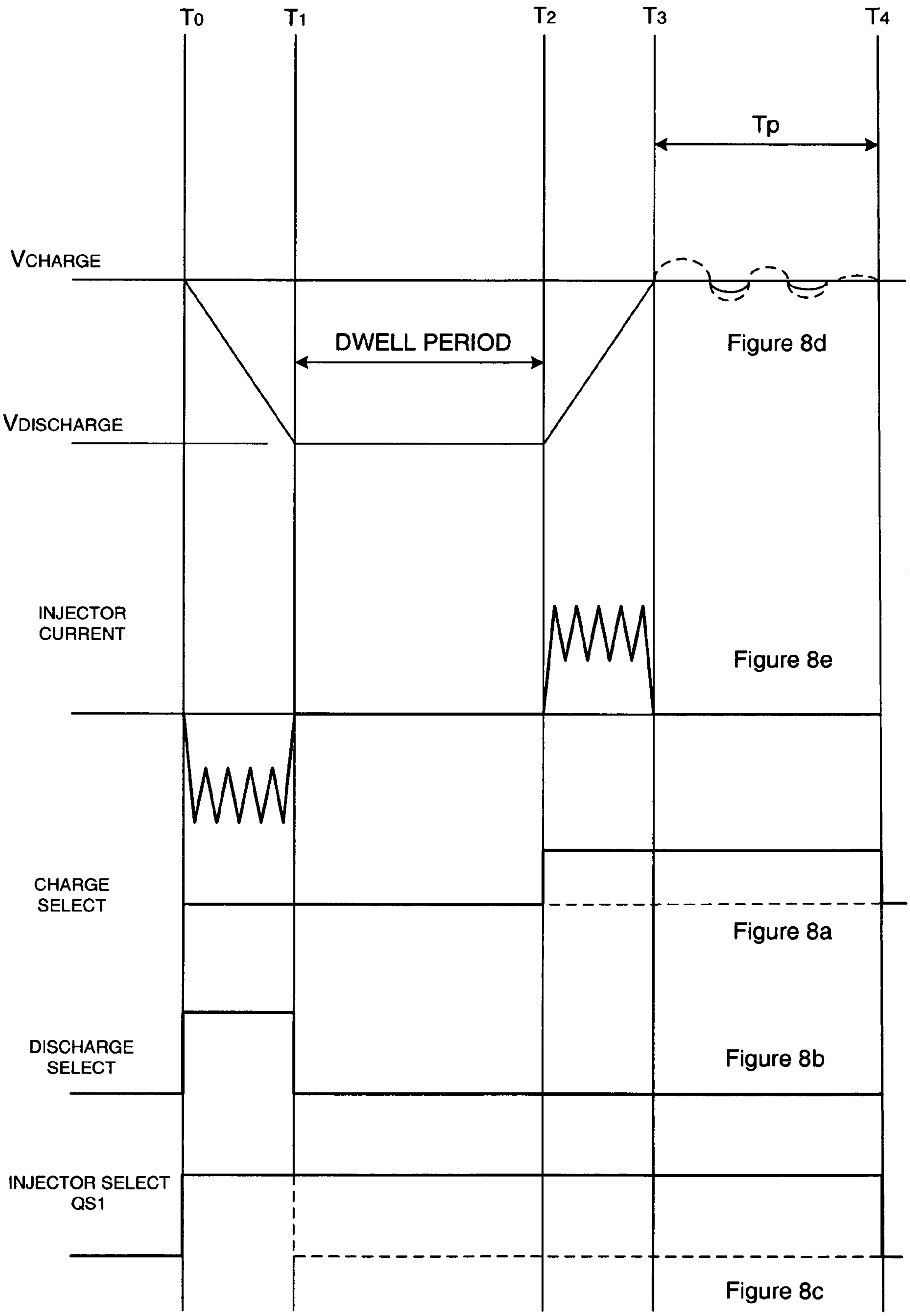

Wait State
300
Injection Command Received from ECU
302
T0
Activate ISQ1
Enable Q1
Apply average discharge current for set time period
304
T1
Deactivate Q1
306
T1 – T2
Maintain V Discharge for
T1 → T2
(Dwell Period)
308
T2 – T3
Activate Q2
(Charge_Select)
Apply average current for set time period
310
T3 – T4
After predetermined period T
Disable Q2
Deactivate QS1
312
Wait State
300

Fig. 7


T0
T1
T2
T3
T4
Tp
VCHARGE
DWELL PERIOD
VDISCHARGE
Figure 8d
INJECTOR
CURRENT
Figure 8e
CHARGE
SELECT
Figure 8a
DISCHARGE
SELECT
Figure 8b
INJECTOR SELECT
QS1
Figure 8c

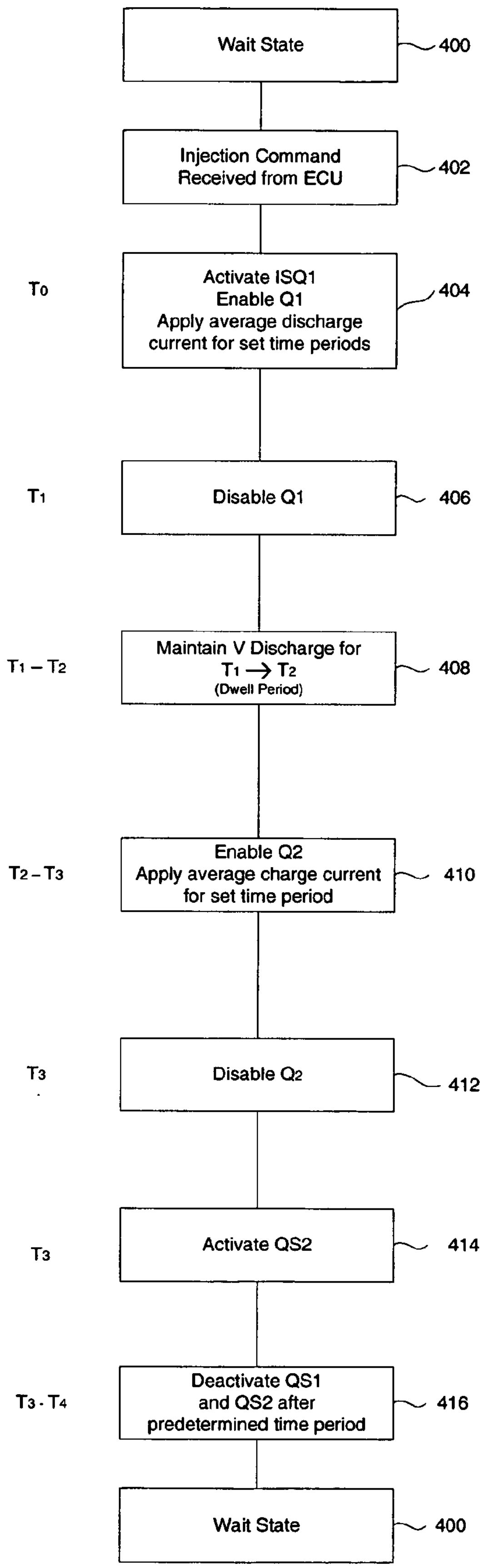
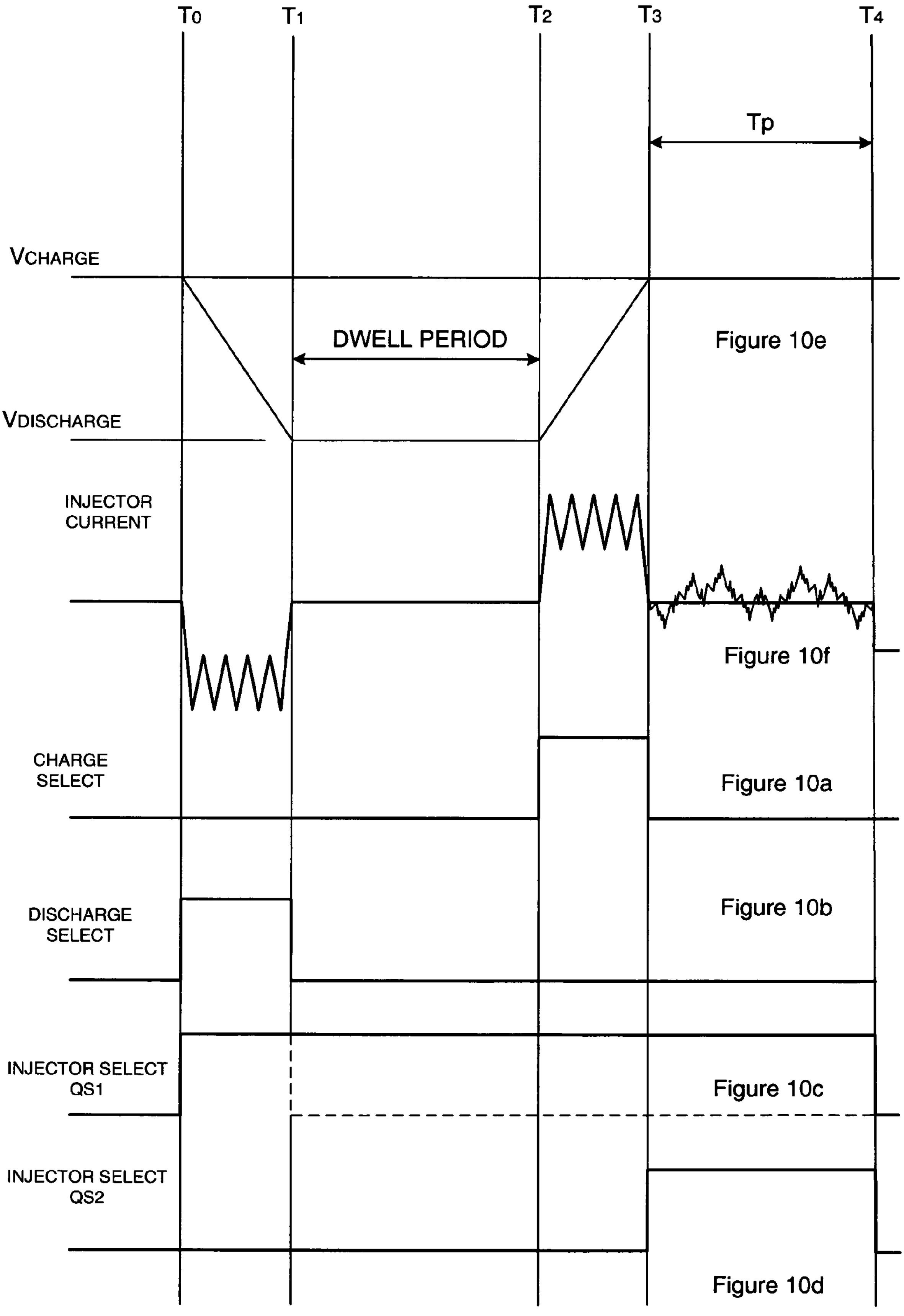

Wait State
400
Injection Command Received from ECU
402
T0
Activate ISQ1
Enable Q1
Apply average discharge current for set time periods
404
T1
Disable Q1
406
T1 – T2
Maintain V Discharge for
T1 → T2
(Dwell Period)
408
T2 – T3
Enable Q2
Apply average charge current for set time period
410
T3
Disable Q2
412
T3
Activate QS2
414
T3 - T4
Deactivate QS1 and QS2 after predetermined time period
416
Wait State
400

Fig. 9


T0
T1
T2
T3
T4
Tp
VCHARGE
DWELL PERIOD
Figure 10e
VDISCHARGE
INJECTOR CURRENT
Figure 10f
CHARGE SELECT
Figure 10a
DISCHARGE SELECT
Figure 10b
INJECTOR SELECT QS1
Figure 10c
INJECTOR SELECT QS2
Figure 10d

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 06 25 4141

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 1 400 677 A (DELPHI TECH INC [US]) 24 March 2004 (2004-03-24) * paragraph [0067]; figure 3 *	1-3,8-15	INV. F02D41/20 H01L41/04
X	EP 1 400 676 A (DELPHI TECH INC [US]) 24 March 2004 (2004-03-24) * paragraphs [0140], [0143] * * figures 9,11 *	1-7, 12-15	
A	WO 2005/028836 A (DELPHI TECH INC [US]; MARTIN STEVEN J [GB]) 31 March 2005 (2005-03-31) * page 8, paragraph 2 *	2,3	

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F02D
H01L

The present search report has been drawn up for all claims

3

Place of search	Date of completion of the search	Examiner
The Hague	6 July 2007	Röttger, Klaus

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06-07-2007

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EP 1400676	A	24-03-2004	EP	1400677	A2	24-03-2004
WO 2005028836	A	31-03-2005	EP	1519024	A1	30-03-2005
			JP	2007506038	T	15-03-2007
			US	2007103033	A1	10-05-2007

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- EP 0955901 B **[0006]**