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(54) Driving circuit for a magnetic valve

(57) The invention relates to a driving circuit for a magnetic valve comprising a comparator with variable hysteresis (30). The comparator with variable hysteresis (30) additional to a measuring input terminal (CMP_IN (+)) and a control input terminal (CMP_IN(-)) has an output terminal (CMP_OUT) and comprises: an operational amplifier (31) having an non-inverting input terminal (+), an inverting input terminal (-) and an output terminal (CMP_OUT), a serial connection comprising a third resistor (34), a second resistor (33), a first resistor (32) and a control voltage source delivering a variable threshold value (V_{ctrl}), the serial connection being connected in parallel to a supply voltage (V_{5V}) whereby a partial serial connection comprising the second resistor (33), the first resistor (32) and the control voltage source being connected in parallel to a further switching element (35) and the point of connection between the second (33) and first (32) resistor being a voltage tap (V_{in}), whereby the inverting input terminal (-) of the operational amplifier (31) being connected with the voltage tap (V_{in}) and the output terminal (CMP_OUT) of the operational amplifier (31) being connected with the control input terminal of the further switching element (35).

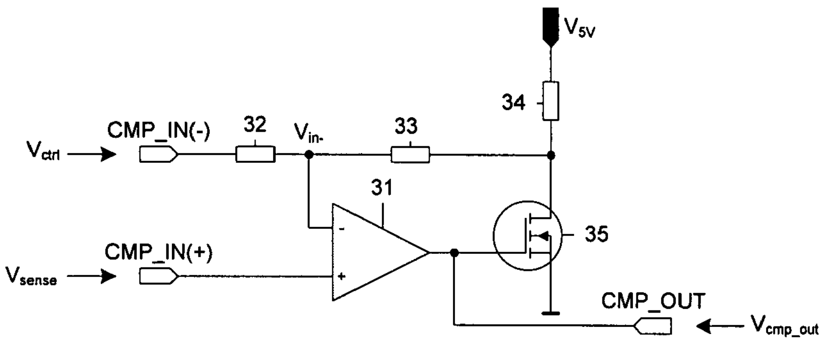

Fig. 4

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Description

[0001] The invention addresses the problem of magnetic valve current control particularly of high pressure fuel pump valve current control.

[0002] A high pressure fuel pump valve is an electromechanical device used for fuel pressure regulation by opening and closing the valve pin. The pin is actuated by an electromagnet. It is fully opened by an electric current passing through its coil and closed when the current is shut off. Therefore the valve behaves as an ON-OFF device. The requirements for the valve control circuitry are the following:

- in order to ensure valve pin opening a minimum current has to pass through the coil,
- to prevent coil saturation the current has to be limited to a maximum value, depending on the coil parameters,
- once the valve opening is done it is desirable to keep the coil current to a minimum to reduce the power dissipation but without affecting the state of the pin,
- valve opening and closing timing is critical so transitory states should be minimized.

[0003] In order to achieve the above targets the strategy of choice is to use peak and hold current control as is shown in fig. 1:

- fast valve opening is done by driving an initial high current I_{pk} through the coil. Coil current I_{LOAD} starts rising and once the pin has opened and the coil current I_{LOAD} has reached the desired high level I_{pk} it is kept in this state for an amount of time needed for the stabilization of the mechanical system (*Peak* phase),
- once the system is stable the current I_{LOAD} is lowered to a lower level I_{hld} which is high enough that the pin is still opened but low enough to minimize the power dissipation (Hold phase) ,
- the valve is closed by shutting off the current.

[0004] To minimize the dissipation in the valve's electronic driver a driving scheme is employed generally consisting of:

- one or more power drivers for the load (usually MOS transistors or smart switches that switch on or off the valve),
- driver(s) / level adapter(s) for the power driver(s),
- a feedback loop for current regulation comprised of:
- a coil current sensing element like a shunt resistor or the resistance R_{DSon} of a saturated MOS transistor,
- an optional voltage amplifier for current sensed voltage,
- comparator (s) for the coil current (usually with hysteresis),
- a logic for driving the power driver, frequency synchronization etc. driven by the above comparator(s),
- a microcontroller for current level setting, timing and synchronization.

[0005] Generally the closed loop works as following: when the driver is turned on the coil current increases and this causes an increased voltage drop across the current sensing element. This voltage drop (optionally amplified) is compared against a high threshold and if it is higher the driver is switched off by the logic driven by the comparator. This will cause a current decrease in the load causing a decreased sensed voltage at the comparator. When the voltage falls under a low threshold the comparator will turn the driver on again through the logic. To establish a high and a low threshold usually a comparator with a hysteresis is used.

[0006] Since according to the above description a two-level-controller is used, the current in each phase is not constant but rippled due to switching. As a result electromagnetic emissions are generated by the high current switching process and the ripple amplitude might affect the valve's pin state. Therefore additional design requirements have to be fulfilled that are limitation of switching frequency and limitation of the ripple current.

[0007] As the load itself is in the current loop it has a significant influence over the two restrictions above either by influencing the current ripple or the switching frequency, depending on the unrestricted one. Additionally, the coil inductance has a significant variation with coil current, pin position and coil temperature. Increased coil current decreases the inductance thus posing a problem either for the peak or hold modes: switching frequency increases in peak mode or ripple increases in hold mode.

[0008] Tackling the above problems can be done in several ways:

- limiting the ripple amplitude. This will reduce the electromagnetic emissions but if the limits are the same for the peak and hold modes this will increase the switching frequency due to load inductance decrease at high currents, shifting upwards the emission spectrum,
- limiting the switching frequency. This will restrain the emission spectrum (no longer load dependent) but at some point will increase the ripple due to the load inductance change effect.

[0009] Based on the above description several implementations exist, briefly presented below:

US 5,748,431 - *Solenoid driver circuit.* The patent discloses a peak and hold driver with current feedback and linearly adjustable current thresholds and hysteresis via PWM from uC. The hysteresis value is tied to the threshold value by a linear relation, which cannot independently be changed. The circuit is using two coil current comparators and additional logic for generating the hysteresis.

US 4,764,840 - *Dual limit solenoid driver circuit.* The patent discloses a peak and hold driver with current feedback and fixed current thresholds and hysteresis. The hysteresis is different for the peak and for the hold and the peak time duration is fixed by hardware.

US 5,784,245 - *Solenoid driver and method for determining solenoid operational status.* The patent discloses a peak and hold driver with current feedback and fixed current thresholds and hysteresis additionally having the capability of solenoid status detection.

US 4,949,215 - *Driver for high speed solenoid actuator.* The patent discloses a peak and hold driver with current feedback and adjustable current thresholds and hysteresis with emphasis on fast transition times of the actuator pin.

US 4,605,983 - *Drive circuits.* The patent discloses a peak and hold driver with current feedback having current feedback amplifier and fixed current thresholds and hysteresis. The hysteresis is different for the peak and for the hold.

[0010] It is an object of the invention to allow adjustable current ripple amplitude control during operation thus tackling the electromagnetic emission level without increasing system complexity.

[0011] A driving circuit for a magnetic valve according to this invention comprises a coil of the valve and serially connected therewith at least one switching element, the control input of the at least one switching element being connected with the output terminal of a comparator with variable hysteresis a measuring input terminal of which being arranged to be supplied with a signal being representative for a current through the coil, and a control input terminal of which being arranged to be supplied with a variable threshold value. The comparator with variable hysteresis additional to the measuring input terminal and the control input terminal has an output terminal and comprises an operational amplifier having an non-inverting input terminal, an inverting input terminal and an output terminal, the comparator further comprises a serial connection comprising a first resistor, a second resistor, a third resistor and a control voltage source, the serial connection being connected in parallel to a supply voltage whereby a partial serial connection comprising the second resistor, the third resistor and the control voltage source being connected in parallel to a further switching element and the point of connection between the second and third resistor being a voltage tap, whereby the inverting input terminal of the operational amplifier being connected with the voltage tap and the output terminal of the operational amplifier being connected with the control input terminal of the further switching element.

[0012] Furthermore according to a preferred embodiment of the invention the variable threshold value of the control voltage source is the output voltage of a low pass filter arranged to be supplied by a PWM-signal. The PWM-signal can be supplied by a microprocessor.

[0013] The present invention will be understood more fully from the detailed description given hereinbelow and from the accompanying drawings of the preferred embodiments of the invention but are for the purpose of explanation and understanding only. In the drawings

Fig.1 shows the time dependence of some essential signals in a closed loop driving circuit,

Fig.2 shows a detailed driver circuit for a magnetic valve,

Fig.3 shows the time dependence of some essential signals in a closed loop driving circuit showing the dependence of the hysteresis from the peak and hold levels,

Fig.4 shows a detailed circuit of an inventive variable hysteresis comparator,

Fig.5 shows the effect of the linear dependency of the hysteresis on the switching levels.

[0014] In figure 2 the load 70 which represents the coil of a valve is driven by a switching element realized by a PMOS transistor 60 which is connected between a battery voltage V_{BAT} and the load 70 and at the same time by a switching element realized by a NMOS transistor 62 which is connected between the load 70 and via a shunt resistor 22 with ground potential having the battery voltage V_{BAT} as supply. Both transistors 60, 62 are enabled by a Low level on a NEN output of a microcontroller 10. The NEN output of microcontroller 10 is connected via an inverter 43 with the gate of NMOS transistor 62 and with an input of a first OR gate 41. The other input of the first OR gate 41 is connected with the output of a second OR gate 40 a first input of this second OR gate 40 is connected with a NON_HS output of microprocessor 10. A second input of the second OR gate 40 is connected with the output of a variable hysteresis comparator 30 which has a hysteresis. The non-inverting input of comparator 30 is connected via a (optional) shunt amplifier 21 with a connection of shunt resistor 22, the inverting input of comparator 30 being connected via a low-pass-filter 20 with a PWM-output of microprocessor 10. The output of the second OR gate 41 is connected via a high-side-driver 42 with the gate of PMOS transistor 60.

[0015] The Low level on the NEN output will make the output of the first OR gate 41 output become Low if the other input coming from the second OR gate 40 is also Low. Low output at the fist OR gate 41 is buffered by high-side-driver 42 so the gate of PMOS transistor 60 will be Low, therefore closing the PMOS transistor 60. At the same time a Low on the NEN output is applied at the input of low-side-inverter buffer 43, its output becoming High and closing the NMOS transistor 62 by driving its gate in a High level. Thus a current path is established: V_{BAT} - transistor 60 - load 70 - transistor 62 - R_{shunt} 22 - GND.

[0016] The coil current I_{LOAD} thus passes through this path, starts rising and causes a voltage drop on shunt resistor 22, proportional to the coil current I_{LOAD}. Further on the voltage drop might pass through the shunt amplifier 21 (amplification factor x10) or can pass on unamplified, yielding a voltage V_{sense}. The amplifier is needed when the voltage drop on 22 is comparable in magnitude to the offset error of the comparator 30, thus reducing the offset's influence.

[0017] The voltage V_{sense} is then passed at the non-inverting input (+) of the variable hysteresis comparator 30. The inverting input (-) of the comparator 30 is fed with a control voltage V_{ctrl} from the PWM output of the microcontroller 10 via a low pass filter 20. Its cutoff frequency must be low enough that the switching ripple of the PWM signal is filtered out at the control voltage V_{ctrl} at the output of the filter 20.

[0018] The control voltage V_{ctrl} is used to set the comparator threshold and at the same time to control the hysteresis of the comparator 30. The output $V_{cmp-out}$ of the comparator 30 is then fed to the first OR gate 40: a Low at output $V_{cmp-out}$ together with a Low at output NON_HS will cause a Low on the output of the second OR gate 40 thus turning ON PMOS transistor 60 while a High level on one of the output $V_{cmp-out}$ of the comparator 30 or the NON_HS output will turn off the PMOS transistor 60. when the PMOS transistor 60 is turned off the current flowing through it is interrupted but since the coil 70 is still energized it will cause a drop in the potential of the cathode of a freewheeling diode 61 that low that the diode starts directly conducting. The current path for the coil current I_{LOAD} is now diode 61 - load 70 - NMOS transistor 62 - R_{shunt} 22 - and through GND back to diode 61 (long dashed current path in fig. 2). In this phase I_{LOAD} falls towards 0A.

[0019] The enabling of the NEN output (= LOW level) is done when the valve has to be opened and hence the coil energized. At this moment the coil current I_{LOAD} is 0A as well as the voltage drop V_{sense} at shunt resistor 22 is 0V while the output V_{ctrl} of low pass filter 20 is at the desired peak phase level (V_{peak}) which is shown in fig. 3. Thus the output $V_{cmp-out}$ of comparator 30 is Low as well as the NON_HS output of microprocessor 10 causing both transistors 60 and 62 to be closed. The coil current I_{LOAD} starts rising, its rise time roughly depending on load parameters (modeled as L_L and R_L) and battery voltage V_{BAT}. At some point the valve pin is opened which is seen as an I_{LOAD} slope change due to different L_L. The coil current I_{LOAD} further rises until the high level of the peak phase I_{pk_H} is reached. At this point the measuring voltage V_{sense} has reached the high threshold V_{peak} of comparator 30 set by the signal V_{ctrl} and the output $V_{ctrl-out}$ of comparator 30 becomes High. As described above, this causes the PMOS transistor 60 to turn off and the load 70 to be discharged via diode 61 freewheeling path causing a drop of the coil current I_{LOAD} down to the low level I_{pk-L} of peak phase. At this point the voltage V_{sense} has reached the low threshold V_{peak} of comparator and the output $V_{ctrl-out}$ of comparator 30 becomes Low, switching on again PMOS transistor 60 and causing the coil current I_{LOAD} to increase. Thus a free running oscillatory closed loop is formed where the coil current I_{LOAD} oscillates between I_{pk_H} and I_{pk_L} as can be seen in fig. 3. The oscillation frequency is determined by the above mentioned I_{LOAD} thresholds, V_{BAT} and load characteristics (L_L and R_L) .

[0020] Once the mechanical system of the valve is stabilized, the peak phase ends and the microcontroller 10 changes the duty cycle at the PWM output causing a voltage drop at the output V_{ctrl} of low pass filter 20 down to a value V_{Hold}. The new value V_{Hold} changes the hysteresis thresholds of the comparator 30 causing new current thresholds I_{hld_H} and I_{hld-L} (by the same mechanism as described for the peak phase) . The coil current I_{LOAD} oscillates in the hold phase between the above mentioned thresholds, determining a new oscillation frequency together with V_{BAT} and the new load parameters (L_L and R_L) .

[0021] By means of the characteristics of comparator 30 which will be further detailed, there is a linear relation between the variable threshold value V_{ctrl} of the control voltage source and comparator hysteresis: the lower the value V_{ctrl} of the control voltage source the lower the hysteresis and vice versa. Thus a high value V_{ctrl} of the control voltage source, corresponding to the high current threshold I_{pk_H} of the peak phase, will cause a high current hysteresis while a lower value V_{ctrl} of the control voltage source, corresponding to the high current threshold I_{hld-H} of the hold phase, will cause a lower proportional current hysteresis. This can be seen in fig. 3: $\Delta I_{pk} = I_{px\_H} - I_{pk\_L}$ is higher than $\Delta I_{hld} = I_{hld-H} - I_{hid-L}$ and at the same time the oscillation frequency of the coil current I_{LOAD} is changed. In the same figure a different shape of the value V_{ctrl} of the control voltage source (dashed line) will cause a different profile of the coil current I_{LOAD} (dashed line), supporting the same argument.

[0022] This characteristic of the comparator namely decreased hysteresis with decreased threshold value V_{ctrl} of the control voltage source is useful as the inductance L_L of the load 70 changes: the higher the coil current I_{LOAD} the lower the inductance L_L. The target is to keep the oscillation frequency under control when the high current I_{PK-H} of the peak phase will cause a decrease of the inductance L_L of the load 70:

- hold phase - low current => high inductance L_L and lower current hysteresis,
- peak phase - high current => small inductance L_L => increased oscillation frequency, but due to increased

current hysteresis the frequency is lowered thus compensating for smaller inductance L_L.

[0023] According to fig. 4 the variable hysteresis comparator 30 is comprised of a classical push pull comparator 31 and a positive voltage feedback path: resistors 32, 33 and 34 and NMOS transistor 35. The value V_{ctrl} of the control voltage source is applied at the inverting input CMP_IN(-), the coil current feedback measuring voltage V_{sense} is applied at the non-inverting input CMP_IN(+) and the output of the comparator 30 is taken from the output CMP_OUT of the comparator 31.

[0024] The first pin CMP_IN(-)is connected with the inverting input of the comparator 31 via a first resistor 32. The inverting input of the comparator 31 is also connected via a second resistor 33 and a third resistor 34 with a supply voltage V_{5v}. The connection node between the second and the third resistors 33, 34 is connected via the conducting path of a NMOS transistor 35 as a further switching element with ground potential while the gate of the transistor 35 is connected with the output of comparator 31.

[0025] Assuming a given value V_{ctrl} of the control voltage source at the first pin CMP_IN(-) and a low level of the coil current feedback measuring voltage V_{sense} at the second pin CMP_IN (+) so that the output CMP_OUT is Low this will cause transistor 35 to be opened and the feedback path will be: second and third resistors 33 and 34 connected between the inverting input and the 5V supply voltage V_{5v}. The resistor divider first resistor 32 and second and third resistors 33 + 34 will cause the potential at the inverting input of the comparator 31 to be higher than the control voltage V_{ctrl} due to pull up to V_{5V}, thus establishing the high threshold. When CMP_IN (+) potential starts rising and reaches the high threshold the output CMP_OUT will become high, closing at the same time the further switching element 35. The feedback path will be in this case only resistor 33 between the inverting input and GND (via low R_{DSon} of the closed transistor 35). The resistor divider 32 and 33 will cause the potential at the inverting input to be lower than V_{ctrl} due to pull down to GND, thus establishing the low threshold. The output CMP_OUT will become Low again when CMP_IN (+) will become lower than the low threshold. The characteristic of the comparator 30 can be seen in fig. 5b. Due to the fact that the feedback path of comparator 31 contains different resistors for the two states of the output CMP_OUT (resistors 33 + 34 when Low and resistor 33 when High) the hysteresis value $\Delta = V_H - V_L$ will linearly increase as the control voltage V_{ctrl} increases, thus achieving the needed characteristic of the high pressure fuel pump loop: higher current hysteresis in peak mode and lower current hysteresis in hold mode according to fig. 5a.

Claims

1. Driving circuit for a magnetic valve comprising a coil (70) of the valve and therewith serially connected at least one switching element (60),
   the control input of the at least one switching element (60) being connected with the output terminal (CMP_OUT) of a comparator with variable hysteresis (30) a measuring input terminal (CMP_IN (+)) of which being arranged to be supplied with a signal being representative for a current (I_{LOAD}) through the coil (70), and a control input terminal (CMP_IN(-)) of which being arranged to be supplied with a variable threshold value (V_{ctrl}), **characterised in that** the comparator with variable hysteresis (30) additional to the measuring input terminal (CMP_IN(+)) and the control input terminal (CMP_IN(-)) has an output terminal (CMP_OUT) and comprises:

   an operational amplifier (31) having an non-inverting input terminal (+),an inverting input terminal (-) and an output terminal (CMP_OUT) ,
   a serial connection comprising a third resistor (34), a second resistor (33) , a first resistor (32) and a control voltage source delivering a variable threshold value (V_{ctrl}), the serial connection being connected in parallel to a supply voltage (V_{5V}) whereby a partial serial connection comprising the second resistor (33), the first resistor (32) and the control voltage source being connected in parallel to a further switching element (35) and the point of connection between the second (33) and first (32) resistor being a voltage tap (V_{in}) ,
   whereby the inverting input terminal (-) of the operational amplifier (31) being connected with the voltage tap (V_{in}) and the output terminal (CMP_OUT) of the operational amplifier (31) being connected with the control input terminal of the further switching element (35).

2. Driving circuit according to claim 1, **characterized in that** the variable threshold value (V_{ctrl}) of the control voltage source is the output voltage of a low pass filter (20) arranged to be supplied by a PWM-signal .

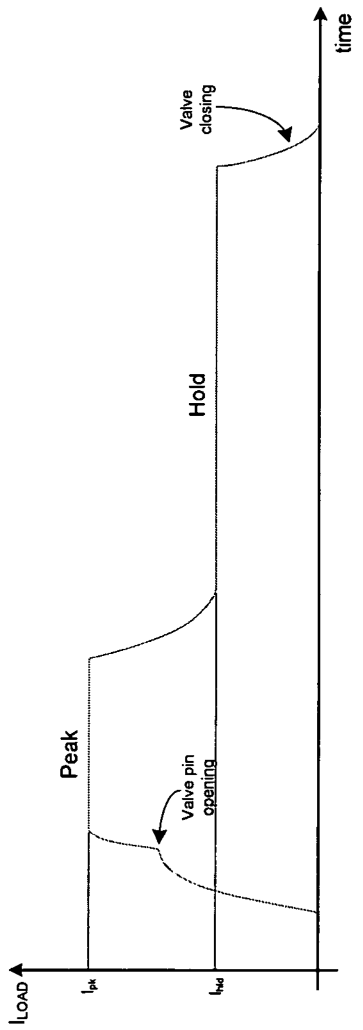
I_LOAD
I_pk
I_hld
Peak
Valve pin opening
Hold
Valve closing
time

Fig. 1

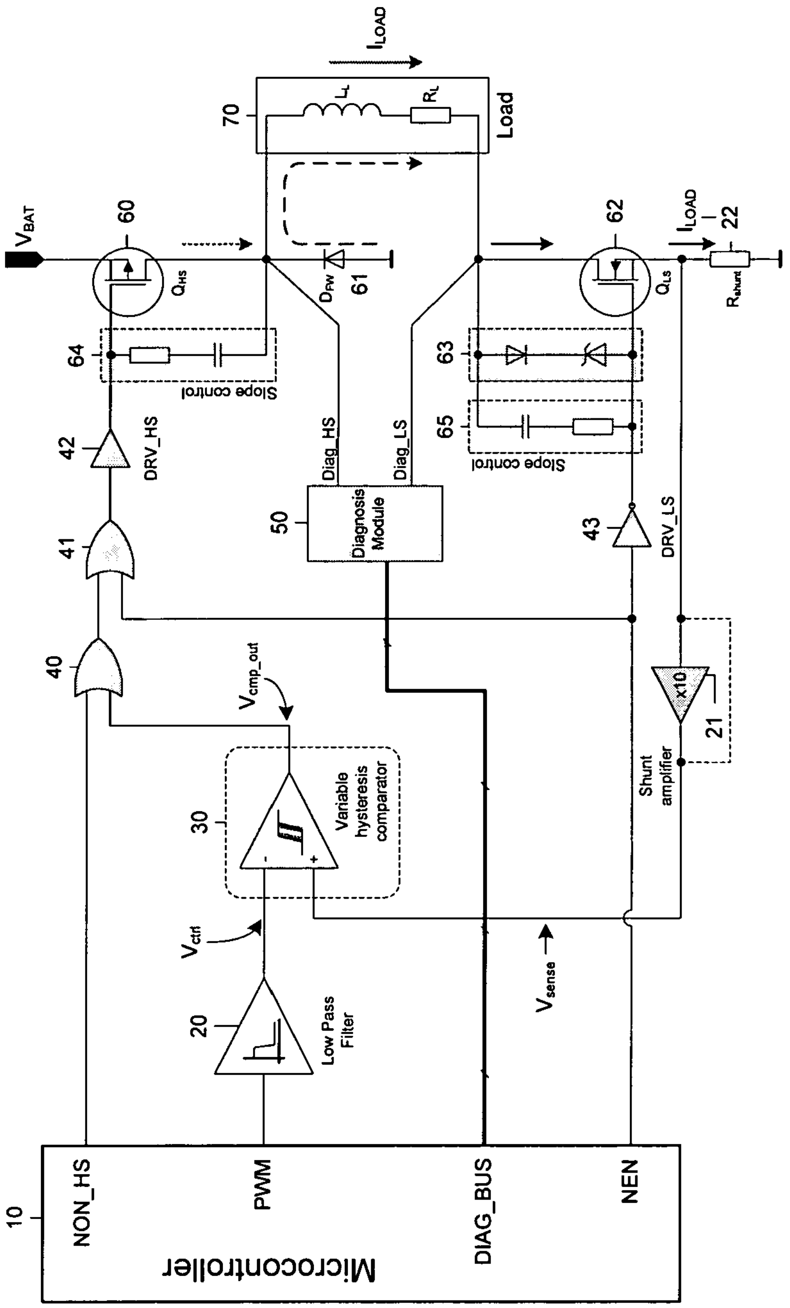
Microcontroller
10
NON_HS
PWM
DIAG_BUS
NEN
20
Low Pass Filter
Vctrl
30
Variable hysteresis comparator
Vcmp_out
Vsense
40
41
42
DRV_HS
43
DRV_LS
50
Diagnosis Module
Diag_HS
Diag_LS
64
Slope control
65
Slope control
63
VBAT
60
QHS
DFW
61
62
QLS
70
LL
RL
Load
ILOAD
22
Rshunt
21
x10
Shunt amplifier

Fig. 2

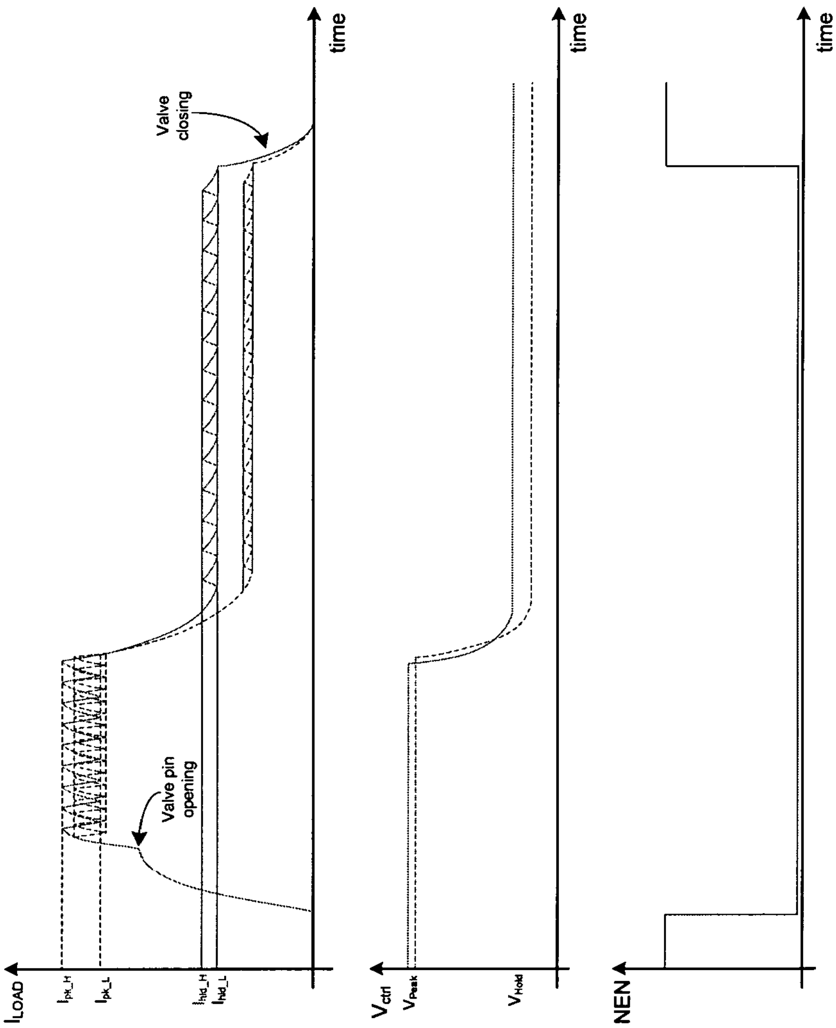
time
Valve closing
Valve pin opening
ILOAD
Ipk_H
Ipk_L
Ihld_H
Ihld_L
Vctrl
VPeak
VHold
NEN

Fig. 3

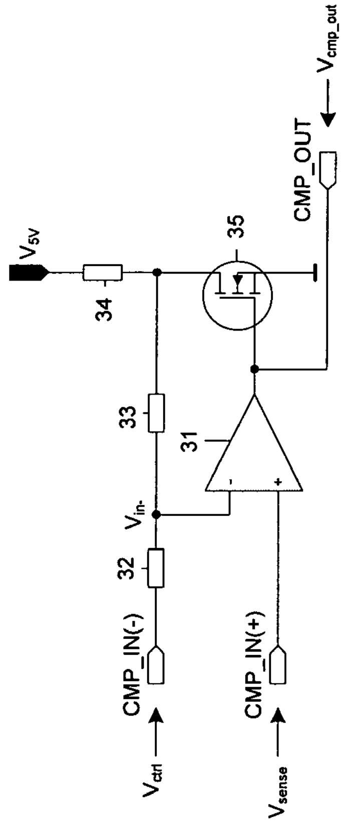
V5V
34
35
CMP_OUT
Vcmp_out
33
31
Vin-
32
CMP_IN(-)
CMP_IN(+)
Vctrl
Vsense

Fig. 4

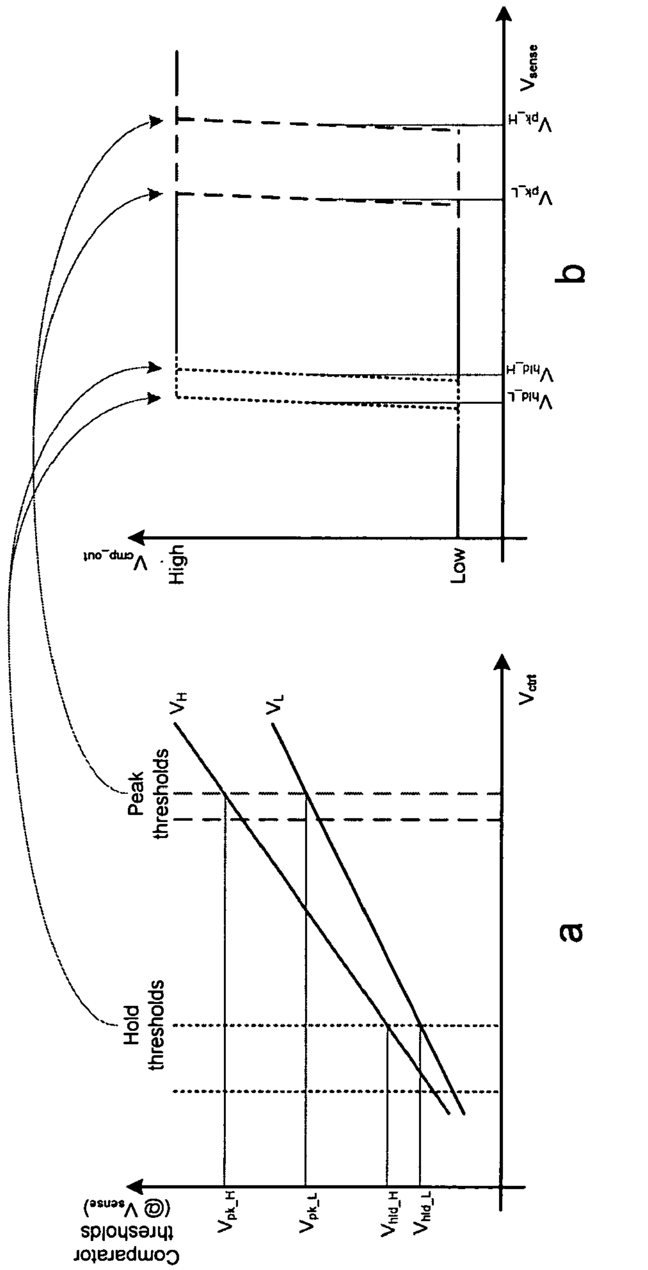
a
b
Comparator thresholds (@ V_sense)
V_pk_H
V_pk_L
V_hld_H
V_hld_L
V_H
V_L
V_ctrl
Peak thresholds
Hold thresholds
V_cmp_out
High
Low
V_sense

Fig. 5

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EUROPEAN SEARCH REPORT

Application Number
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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	11 October 2012	Wettemann, Mark

CATEGORY OF CITED DOCUMENTS

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The members are as contained in the European Patent Office EDP file on
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