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(71) Applicant: **MAGNETI MARELLI SISTEMI ELETTRONICI S.p.A.**
20011 Corbetta (Milano) (IT)

(72) Inventor: **Nepote, Andrea**
10131, TORINO (IT)

(74) Representative: **Deambrogi, Edgardo**
Corso Emilia 8
10152 Torino (IT)

(54) Control circuit and method for a proportional solenoid valve, particularly for use on motor vehicles

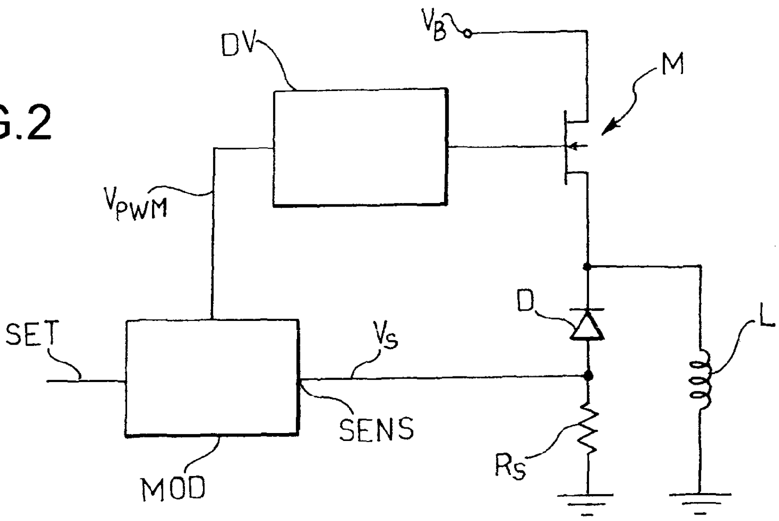
(57) What is described is a control circuit for a solenoid valve having a control winding or solenoid (L), comprising:

- a drive branch provided with a switching device (M) for selectively connecting the winding (L) of the solenoid valve to a source of continuous supply voltage (V_B);
- a branch for recirculating the transient discharge current which is established whenever the winding (L) is disconnected from the source; and
- a resistor (R_S) for sensing the current flowing in the winding (L), located in the recirculation branch and connected to a conductor maintained at a reference potential.

The control method proposed by the invention comprises the steps of:

- connecting the winding (L) to the source of continuous supply voltage (V_B) for an activation time interval having a predetermined fixed duration (T_{ON}); and
- breaking the connection between the winding (L) and the said source for an inactivation time interval of variable duration (T_{OFF}), modulated by the comparison of the transient discharge current flowing in the winding (L) and a threshold value indicating a desired value of excitation current.

FIG.2



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Description

[0001] The present invention relates to a control circuit and method for a proportional solenoid valve provided with a control winding.

[0002] Solenoid valves of the proportional type can be used on motor vehicles, for example for controlling actuator devices in automatic gearboxes or in attitude control systems.

[0003] In a solenoid valve of this type, the control action is proportional to the intensity of the electrical signal exciting the control winding. For the purposes of the control of the excitation signal, the solenoid valve can be likened to an inductive load.

[0004] In applications such as the control of an automatic gearbox, the solenoid valve is typically excited with a sinusoidal current signal having a frequency of the order of 250 Hz. This signal is controlled in PWM mode by a control and drive circuit which is required to maintain a low current ripple around the mean value and a good frequency response. The control and drive circuit must also be designed to provide protection against short circuits to ground and/or battery, and preferably to provide diagnosis of short-circuit or open-circuit conditions on the load.

[0005] The construction of a complete control circuit for a solenoid valve requires the specification of both the circuit design of the power section and the control mode of the PWM signal for driving the latter.

[0006] There is a known way of using a drive circuit configuration with two switches (high-side/low-side) and a floating solenoid valve, illustrated in Figure 1a. The solenoid valve, identified in a general way below as an inductive load L, is connected to a continuous voltage power source V_B (the vehicle battery, for example) and to a conductor placed at a reference potential (ground), through a first switch SW_H and a second switch SW_L respectively. A diode D in antiparallel recirculates the current in the discharge phase, when the load is not supplied. A current sensing resistor with a low ohmic value is conveniently connected in series with the load to detect the current flowing through it, by differential reading for example, thus enabling the mean or peak current to be controlled.

[0007] This solution has the drawback of being expensive, because of the use of two switches to protect the solenoid valve, in a floating configuration, from short circuits to ground and battery.

[0008] In order to reduce costs, the two solutions shown in Figures 1b and 1c have been proposed in the prior art, both of these solutions making use of a single switch.

[0009] The control circuit configuration of Figure 1b ("Low-side" drive) uses the switch SW_L only, and the solenoid valve is permanently connected to the power source. A current sensing resistor is conveniently connected in series with the switch SW_L to detect the current flowing through the load during the conducting period.

[0010] This configuration has the drawback of exposing the load to evident risks of excess current and to undesired actuation in case of a short circuit to ground.

[0011] The control circuit configuration which is conventionally used is shown in Figure 1c ("High-side" drive); this requires the use of the switch SW_H only, and the solenoid valve is permanently connected to ground.

[0012] For applications in which a high precision of current measurement is not required and in which it is possible to operate at low frequency (in other words when a large current ripple is acceptable in the excitation signal or a highly inductive load is present), the typical solution is to use a "Smart Power" switching device made in MOSFET technology in the form of a floating-source n-channel transistor with an integrated control circuit (current mirror circuit configuration for reading the current flowing in the MOSFET).

[0013] A first drawback of the aforementioned solution is the limited switching speed of the MOSFET drive switch. The activation time of the MOSFET typically ranges from 30 to 150 microseconds, whereas it would be preferable to have switching times of the order of 1 microsecond or less, to avoid excessive power dissipation during the switching edges of the PWM control signal (which in some applications has a frequency of up to 20 kHz).

[0014] A further drawback is the low precision of current measurement (errors of the order of 10%), which is insufficient to meet the specifications of the desired application (errors of the order of 1%). In a disadvantageous way, since this measurement is performed directly in the MOSFET by means of an integrated current mirror, the result is a function of the operating temperature and of the absolute value of the current itself.

[0015] For applications requiring high switching speed and precise current measurement, it is therefore preferable to use a discrete technology MOSFET switching device, with a separate associated control circuit.

[0016] To produce such a configuration, the best solution in terms of control technology is to provide a current sensing resistor in series with the solenoid valve and connected to ground, to detect the current flowing in the load both during the activation state (ON) and during the inactivation state (OFF) of the switching device.

[0017] However, the Applicant considers that this solution is unsuitable, because of the reliability requirements of the application.

[0018] This is because the interposition of such a resistor between the solenoid valve control winding and ground means that the load is a floating load, and, if the control circuit is embedded in an on-board control unit (controller), this configuration makes it necessary to provide two terminals (pins) on the control unit for connection to the external load. Moreover, it becomes impossible to protect the connection terminal on the cold side of the load from short circuits to the battery, unless a further switching device is added, which would nullify all the efforts made to produce a low-cost configuration.

[0019] In an alternative configuration, used at the present time, the current sensing resistor is connected in series with the MOSFET switching device and upstream or downstream of it.

[0020] This configuration makes it possible to measure the current in the load during the activation (ON) phase of the switch, and therefore to implement direct control of the peak current value and evaluation of the mean current by using estimators. However, it is necessary to tackle the problem of the differential reading of the voltage signal at the terminals of the sensing resistor, this signal not being referred to ground, but being superimposed on a common-mode voltage corresponding substantially to the value of the voltage supplied by the power supply battery where the resistor is upstream of the MOSFET, or floating between the supply voltage and the ground reference potential where the resistor is downstream of the MOSFET.

[0021] The difficulty of the rejection of the common-mode voltage (whose value is greater by at least two orders of magnitude than the voltage being measured) results in a low precision of measurement in this case as well.

[0022] The object of the present invention is to provide a solution which overcomes the problems described above, and specifically to provide a control circuit configuration for a proportional solenoid valve which is of relatively low cost, but which is suitable for generating an excitation signal for the control winding of the solenoid valve which has a low ripple about the mean value and a good frequency response, with protection from short circuits to ground and/or battery and diagnosis of short-circuit or open-circuit conditions on the load.

[0023] According to the present invention, this object is achieved by means of a control circuit having the characteristics claimed in Claim 1 and a method having the characteristics claimed in Claim 9.

[0024] Specific embodiments of the invention are defined in the dependent claims.

[0025] Further characteristics and advantages of the invention will be disclosed more fully in the following detailed description of one embodiment of the invention, provided by way of example and without restrictive intent, with reference to the attached drawings, in which:

Figures 1a, 1b and 1c are circuit diagrams showing different embodiments of a control circuit for a proportional solenoid valve according to the prior art;

Figure 2 is a diagram, partially in block form, showing the configuration of the control circuit according to the invention;

Figure 3 is a detailed circuit diagram relating to a drive device of the circuit of Figure 2;

Figure 4 is a detailed circuit diagram relating to an arrangement for modulating the drive signal of the circuit of Figure 2;

Figure 5 is a variant of the circuit diagram of the modulation arrangement of Figure 4; and

Figure 6 is a set of diagrams showing examples of the variation, as a function of time shown on the horizontal axis, of some signals generated during the operation of the control circuit of Figure 2.

[0026] A proportional solenoid valve and an associated control circuit are shown schematically in Figure 2. Elements or components identical or functionally equivalent to those shown in Figures 1a, 1b and 1c relating to the prior art have been indicated with the same references.

[0027] The proportional solenoid valve is of the type comprising a control winding or solenoid and a moving element (not shown) for implementing the control, the position of this element being controllable as a function of the intensity of the excitation current supplied to the winding. In the remainder of the description, the valve is represented as an inductive load L, having a first terminal connected permanently to a conductor maintained at a reference potential (ground) and a second terminal connected to a connecting terminal (pin) of a control circuit advantageously incorporated in a single on-board electronic control unit (ECU).

[0028] In practice, the ground connection is made by direct connection to a point on the vehicle's body, or through a return line to the control unit (ECU) to a corresponding ground terminal, for which no protection is required against short circuits to the battery.

[0029] In the illustrated example of embodiment, the control circuit comprises a drive branch connected to the control winding of the solenoid valve. The drive branch includes a MOSFET power switch device, indicated by M, connected to a source of continuous supply voltage (V_B) such as the on-board battery of a motor vehicle, and capable of being driven in ON-OFF mode at its gate terminal. A current recirculation branch comprising a recirculation device such as a diode D is connected in parallel with the load L.

[0030] A current sensing resistor R_S is advantageously connected in the recirculation branch, between the anode terminal of the recirculation diode D and the conductor at ground potential of the control unit (ECU). This arrangement provides intrinsic protection from short circuit to the battery for the terminal connected to the recirculation diode, owing to the presence of the aforesaid diode.

[0031] The terminal of the current resistor R_S opposite the ground conductor is connected to a first input SENS of a circuit for modulating the drive signal of the switching device, indicated by MOD, the output of which is connected to the input of a circuit for driving this switch, indicated as a whole by DV.

[0032] The modulation circuit MOD is designed to generate at its output a control signal with a modulated pulse width V_{PWM} which, after being processed suitably by the drive circuit DV (by having its voltage increased, for example), is applied to the gate terminal of the MOSFET M.

[0033] The modulator circuit MOD also has a second input, indicated by SET, for receiving a signal indicating the desired intensity of the excitation signal (in other words, the desired degree of activation of the solenoid valve), for example from an associated microcontroller which is preferably located in the said control unit.

[0034] A p-channel or an n-channel MOSFET can be used alternatively as the power MOSFET component.

[0035] In the latter case, in which the MOSFET has its source terminal connected to the load, the corresponding drive circuit DV includes a bootstrap circuit, as shown in the attached Figure 3. This comprises a driver DR for the MOSFET, this driver receiving at its input the signal V_{PWM}, conveniently processed by an interface circuit LS for the level shift. A bootstrap capacitor C, connected to the source of supply voltage V_B through a diode D1, is connected across the supply terminals of the driver DR, and has one terminal connected to the source terminal of the MOSFET.

[0036] When the MOSFET is switched off, the bootstrap capacitor C is charged by a current flowing from the power supply source through the diode D1 and the load L towards ground. When the MOSFET becomes conducting, it brings its source terminal to a voltage close to that of the source. The bootstrap capacitor is designed so as to provide a sufficient voltage between gate and source to keep the MOSFET conducting when it receives a conduction control signal. In the next cycle, the capacitor recovers the charge lost by the transfer of the said charge to the gate, by dissipation across the resistive elements of the driver and by dispersion.

[0037] An example of embodiment of the MOD modulation circuit is shown schematically in Figure 4.

[0038] A signal amplifier block AMP is provided in series with the SENS input, this block being formed by a feedback-controlled operational amplifier whose output is connected to the inverting input of a first threshold comparator COMP1. The non-inverting input of the comparator coincides with the second input SET of the modulating circuit.

[0039] The output of the aforesaid comparator is connected to a control input of a monostable device, indicated by MS, of the type which can generate a pulse of predetermined duration T_{ON} on detection of a signal edge at its control input.

[0040] The output of the monostable device is also connected to its control input through a feedback path comprising a second threshold comparator COMP2, to whose inverting input the signal at the output of the monostable device is applied, and whose non-inverting input is associated with a reference voltage level below the level of the voltage signal emitted by the monostable device (for example because it is obtained from the source of common supply voltage (5V) by division). The feedback path is formed in such a way as to reduce the input signal of the monostable device to zero immediately after its activation, in order to ensure that it is reset even in the situation in which, in the subsequent off period of the switch, the objective current is greater than that present in the recirculation branch, a situation which can occur, for example, if rapid increases in the load current are required.

[0041] A train of pulses generated by the monostable device MS forms the modulated duty cycle control signal V_{PWM} emitted by the modulator circuit MOD.

[0042] In an alternative embodiment of the modulation circuit, shown in Figure 5, the monostable device MS can advantageously be replaced by a circuit device based on the use of two other comparator circuits (COMP2 and COMP4) in cascade, configured according to the prior art so as to reproduce the behaviour of a monostable device, generating a pulse of predetermined duration T_{ON} on the detection of a signal edge at its input.

[0043] This architectural solution can be used to save the cost of the monostable component by using a commercial integrated component such as the LM2901 quadruple comparator made by National Semiconductor, all four of whose independent comparators can thus be used.

[0044] By using the architecture of Figure 5, it is possible to make the non-inverting input of the second comparator (COMP4), normally connected to the common supply voltage (5V), available to the exterior as an adjustment input, indicated by ADJ, for setting the interval T_{ON} of duration of the pulse emitted by the monostable circuit.

[0045] Figure 6 shows examples of the variation of the load current (indicated by I_L), in other words the solenoid valve excitation current, the variation of the voltage (V_S) across the terminals of the sensing resistor R_S, the variation of the corresponding signal V_{COMP} applied to the input of the comparator COMP1 of the modulation circuit, and the variation of the control signal V_{PWM} supplied to the MOSFET drive circuit.

[0046] For the control of the solenoid valve, the switch device M of the drive branch is arranged to couple the load L to the voltage source V_B when it receives an activation signal at its input (the interval T_{ON}), thus causing a flow of current in the load. In the absence of the activation signal (in the interval T_{OFF}), the load L is disconnected from the voltage source and progressively discharges the accumulated energy, thus allowing current to flow in the recirculation branch.

[0047] However, the excitation signal applied to the control winding of the solenoid valve has a triangular-wave variation around the desired nominal mean value (controlled by an associated microcontroller by means of the SET input of the control circuit), with rising edges in the activation (conduction) intervals T_{ON} of the MOSFET and decreasing edges in the inactivation (cut-off) intervals TOFF of the MOSFET.

[0048] The total period of the triangular wave is of the order of 50 microseconds, in other words approximately two orders of magnitude less than the period of the desired excitation signal, whose overall variation is sinusoidal with a frequency of the order of 250 Hz.

[0049] In the inactivation interval T_{OFF}, the current flowing through the resistor R_S is the same as that flowing through the recirculation diode D, and therefore the voltage drop across the resistor is proportional to this current.

[0050] The signal V_S detected across the sensing resistor R_S is therefore zero in the activation intervals, when the current flows from the supply source to the load, and has the variation plotted in the figure in the intervals of inactivation, when the current flows in the recirculation branch. This signal shows a virtually trapezoidal variation, rising to a peak value corresponding to the inactivation edge of the control signal V_{PWM} and reducing its intensity progressively during the inactivation interval T_{OFF}.

[0051] The total current flowing through the load can be estimated from the information about the signal V_S (and therefore about the current I_S flowing through the sensing resistor). The PWM control signal is generated by feedback control of the current in the load, using an innovative modulation procedure with a fixed activation interval and an inactivation interval with threshold.

[0052] The activation interval T_{ON} is set according to the inductance characteristics of the load and the available supply voltage.

[0053] In the inactivation interval, the voltage signal V_S is supplied to the SENS input of the modulation circuit MOD and is converted, by amplification and inversion of sign, to the signal V_{COMP}. Preferably, the operational amplifier on which the amplifier block is based should have a high slew rate in order to be compatible with the duration of the inactivation interval TOFF (in other words it should have a switching time which is shorter by at least one order of magnitude), so that the edges of the signal V_S can be replicated promptly in this interval.

[0054] The signal V_{COMP} is compared in the comparator circuit COMP1 with a threshold value V_{th} supplied to the corresponding SET input. It shows a decreasing trend until the threshold level is reached, at which point the signal emitted by the comparator is switched. The corresponding switching edge is interpreted by the monostable device MS, or by the equivalent circuit arrangement, as a trigger signal, resulting in the output of a new activation pulse with the predetermined duration T_{ON}.

[0055] By contrast with the known procedures, in which the duration of the activation interval is controlled (T_{ON} is variable) and the inactivation interval (T_{OFF}) is fixed, the control method according to the present invention is based on the adjustment of the inactivation interval, which is the only interval in which, due to the proposed circuit architecture, it is possible to have information on the current flowing through the load.

[0056] Advantageously, the current is controlled cycle by cycle (the switching frequency is variable, since the activation time T_{ON} is fixed) and the current control loop does not introduce limitations in terms of bandwidth, so that the maximum operating frequency is limited only by the overall period of the PWM control signal, and therefore by the predetermined fixed duration of the activation period (T_{ON}) - which is possibly adjustable if the configuration of Figure 4 is used - and by the duration of the inactivation period (T_{OFF}), which depends on the value of the peak voltage of V_{COMP} and the value of the threshold voltage V_{TH}.

[0057] In the final analysis, therefore, the bandwidth is determined by the physical characteristics of the load (L) and by the supply voltage (V_B), which affect the maximum derivative of the current with respect to time which can be obtained through the load.

[0058] The control method with a fixed activation period conveniently enables the MOSFET to be driven more easily, since the corresponding activation time is no longer changeable according to the temperature, the supply voltage V_B or the desired current intensity, thus making it possible to optimize the capacitance of the bootstrap capacitor C of the MOSFET drive circuit DV and enabling the MOSFET to be controlled over the whole interval T_{ON}, without making the size of this capacitor too large.

[0059] Advantageously, the circuit configuration proposed by the invention can be used to meet all the following requirements listed in the introduction to the present description, namely:

- connection of the load to ground;
- use of a single switch device, which also protects the floating terminal of the load from short circuits to ground; and
- provision of a current sensing resistor in the load drive circuit without the need to provide an additional external connection terminal (pin) in the on-board electronic control unit.

[0060] Clearly, provided that the principle of the invention is retained, the forms of application and the details of construction can be varied widely from what has been described and illustrated purely by way of example and without restrictive intent, without departure from the scope of protection of the present invention as defined by the attached claims.

Claims

1. Control circuit for a solenoid valve having a control winding or solenoid (L), comprising:

    - a drive branch provided with electronic switching means (M) for selectively connecting the said winding (L) to a source of continuous supply voltage (V_B);
    - a branch for recirculating the transient discharge current, which is established whenever the said winding (L) is disconnected from the source, connected to a conductor maintained at a reference potential; and
    - means (R_S) for sensing the current flowing in the said winding (L),

    characterized in that the said current sensing means (R_S) are located in the aforesaid recirculation branch.

2. Control circuit according to Claim 1, **characterized in that** the said current sensing means comprise a resistor (R_S) having a first terminal connected directly to the said conductor at the reference potential.

3. Control circuit according to Claim 2, **characterized in that** it comprises modulation circuit means (MOD) connected to the said sensor means (R_S), adapted to compare the current sensed by the said sensor means (R_S) with a threshold value, and arranged to supply successive signals (V_{PWM}) for the activation and inactivation of the switch means (M) of the drive branch.

4. Control circuit according to Claim 3, **characterized in that** the said activation signals have a predetermined fixed duration (T_{ON}) and the said inactivation signals have a variable duration (T_{OFF}) and are supplied as long as the current sensed by the said sensor means (R_S) is greater than the said threshold value, the alternating sequence of an activation signal and an inactivation signal forming an overall signal (V_{PWM}) of the modulated duty cycle type.

5. Control circuit according to Claim 3 or 4, **characterized in that** the said modulation circuit means (MOD) comprise a threshold comparator (COMP1) adapted to compare a voltage signal (V_{COMP}) indicating the current flowing through the sensor means (R_S) with a threshold value (V_{th}), and a monostable circuit (MS) adapted to emit a signal pulse of predetermined duration (T_{ON}) whenever the said voltage signal (V_{COMP}) reaches the said threshold value (V_{th}).

6. Control circuit according to Claim 5, **characterized in that** the said threshold comparator (COMP1) has a first input connected to the output of an amplifier circuit (AMP) for the voltage signal (V_S) across the terminals of the sensing resistor (R_S), and a second input (SET) connected to a processing unit adapted to generate a threshold signal (V_{th}) indicating a desired excitation current level in the winding (L).

7. Control circuit according to Claim 5, **characterized in that** the said monostable circuit has a control input (ADJ) for the adjustment of the pulse duration (T_{ON}).

8. Control circuit according to any one of the preceding claims, **characterized in that** the said switch means (M) include an n-channel MOSFET transistor.

9. Control method for a solenoid valve having a control winding or solenoid (L), comprising the steps of:

- connecting the winding (L) to a source of continuous supply voltage (V_B) for an activation time interval (T_{ON}) to cause a flow of excitation current (I_L) in the winding (L); and
- breaking the connection between the winding (L) and the said source for an inactivation time interval (T_{OFF}),

in which the said activation interval has a predetermined fixed duration (T_{ON}) and the said inactivation interval has a variable duration (T_{OFF}), modulated by the comparison of the current (I_L) flowing in the said winding with a threshold value indicating a desired value of excitation current in the winding (L).

10. Method according to Claim 9, **characterized in that** the modulation of the duration of the inactivation interval (T_{OFF}) is carried out by the comparison of the value of the transient discharge current, established whenever the said winding (L) is disconnected from the source, with the said threshold value, the inactivation interval continuing as long as the detected current is greater than the said threshold value.

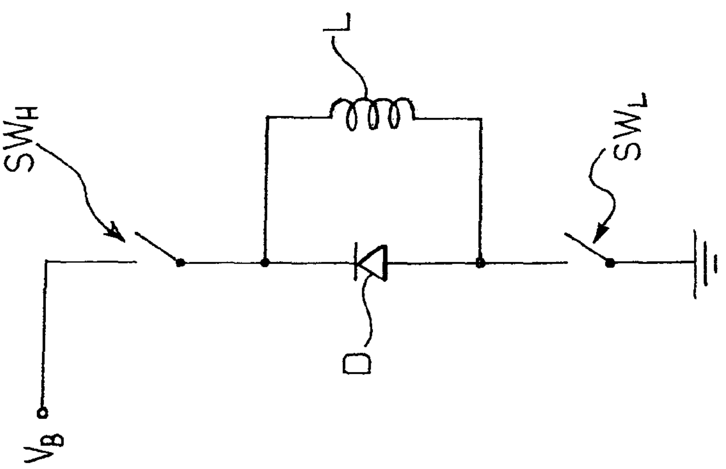


FIG.1a
PRIOR ART

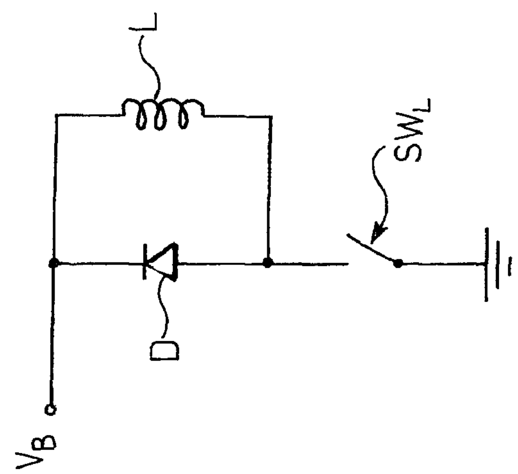


FIG.1b
PRIOR ART

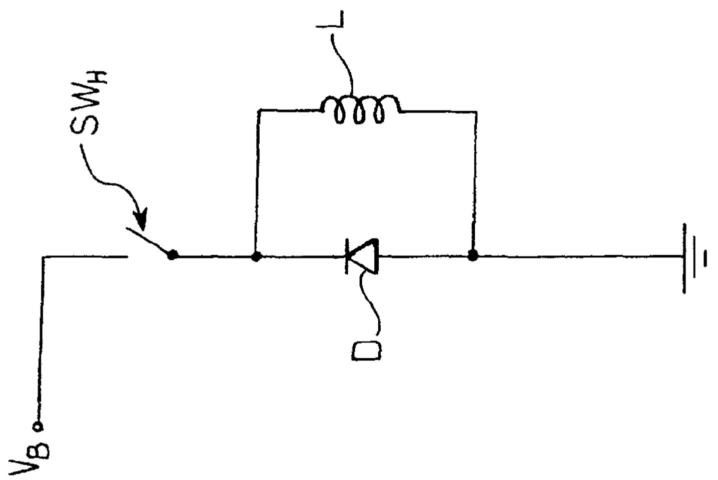


FIG.1c
PRIOR ART

FIG.2

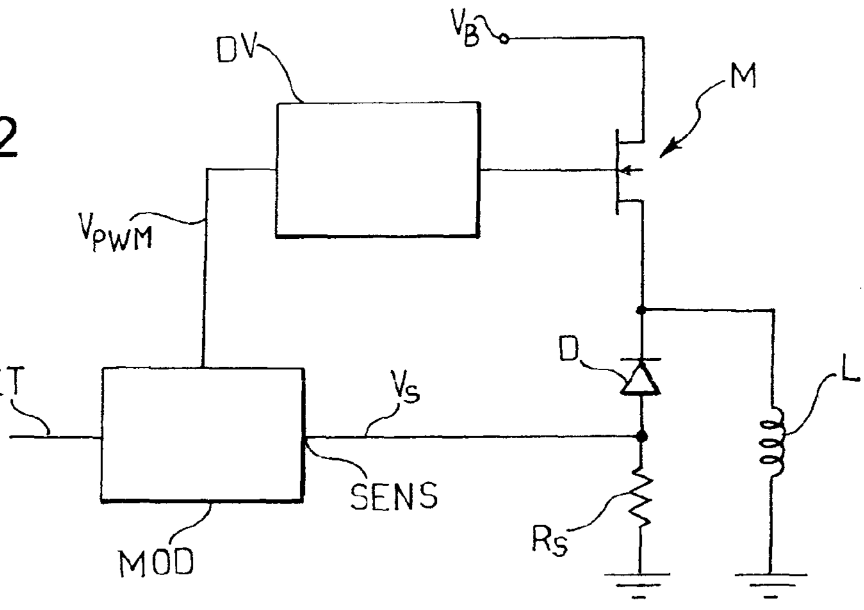
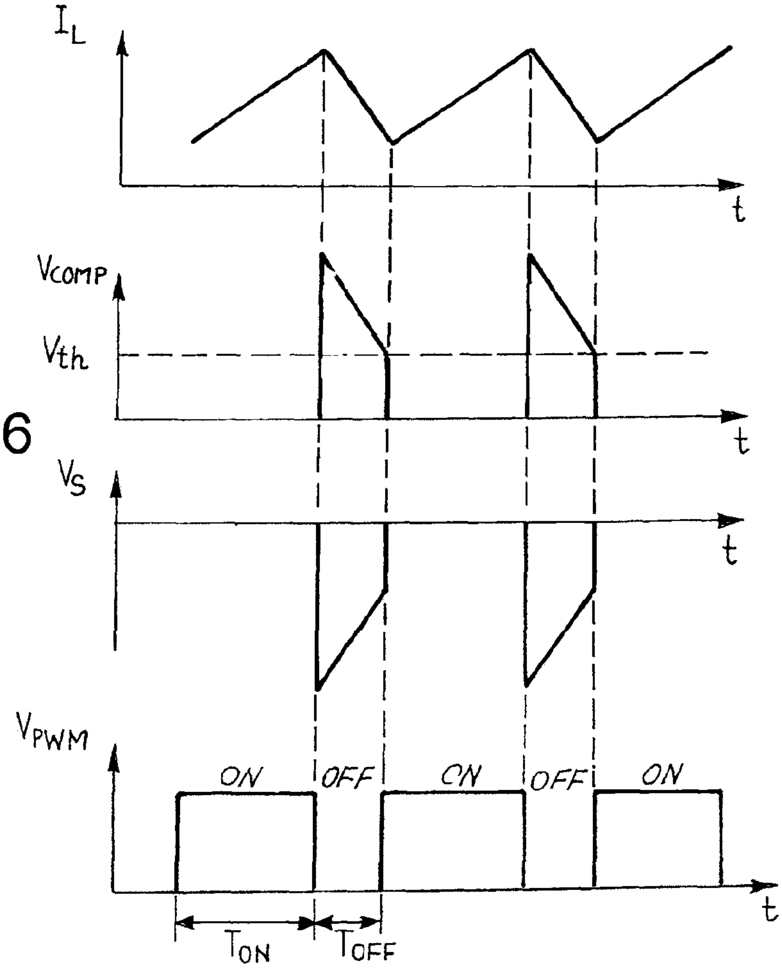

DV
VB
M
VPWM
D
SET
Vs
L
SENS
Rs
MOD

FIG.6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t
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FIG.3

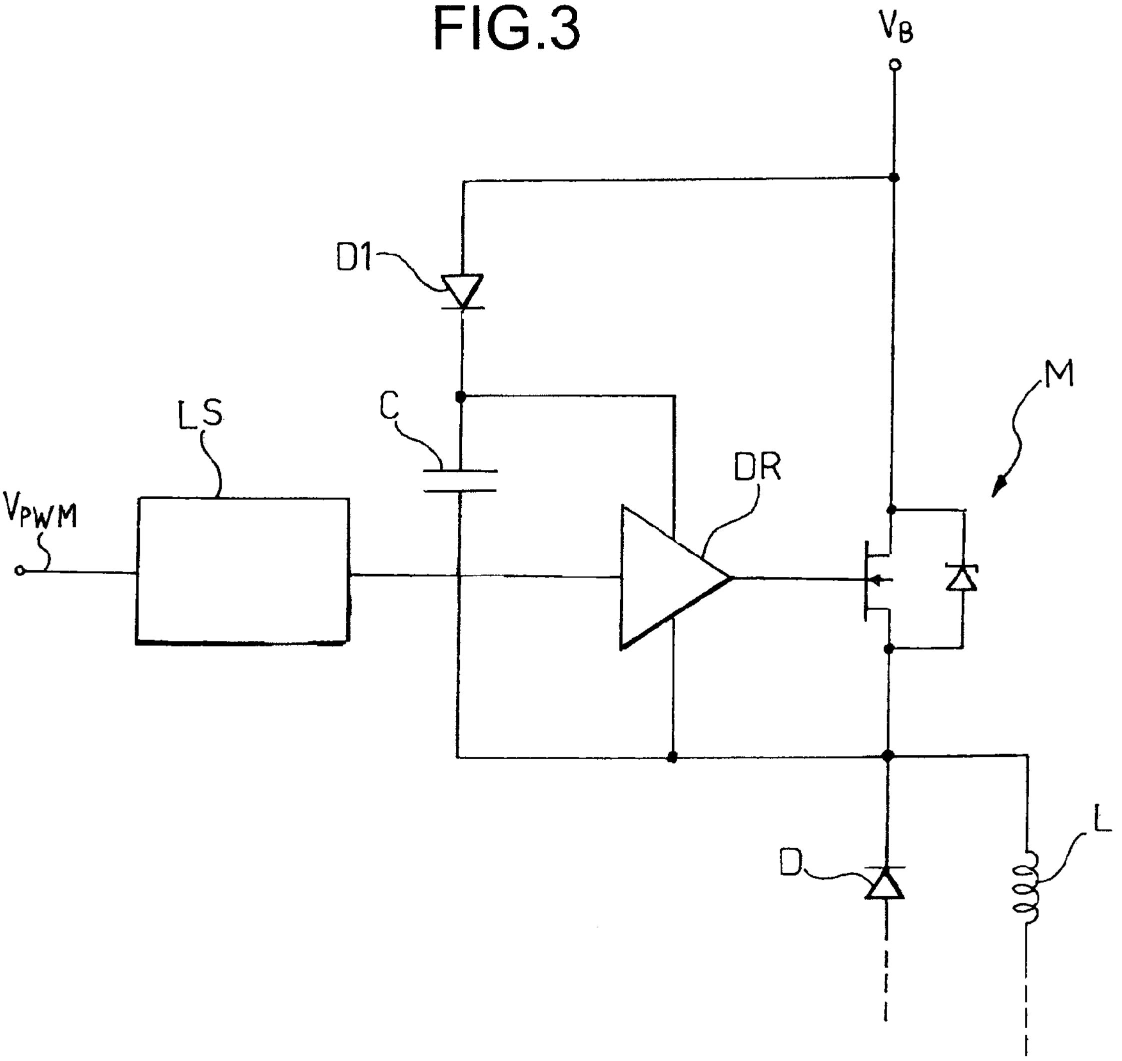


FIG.4

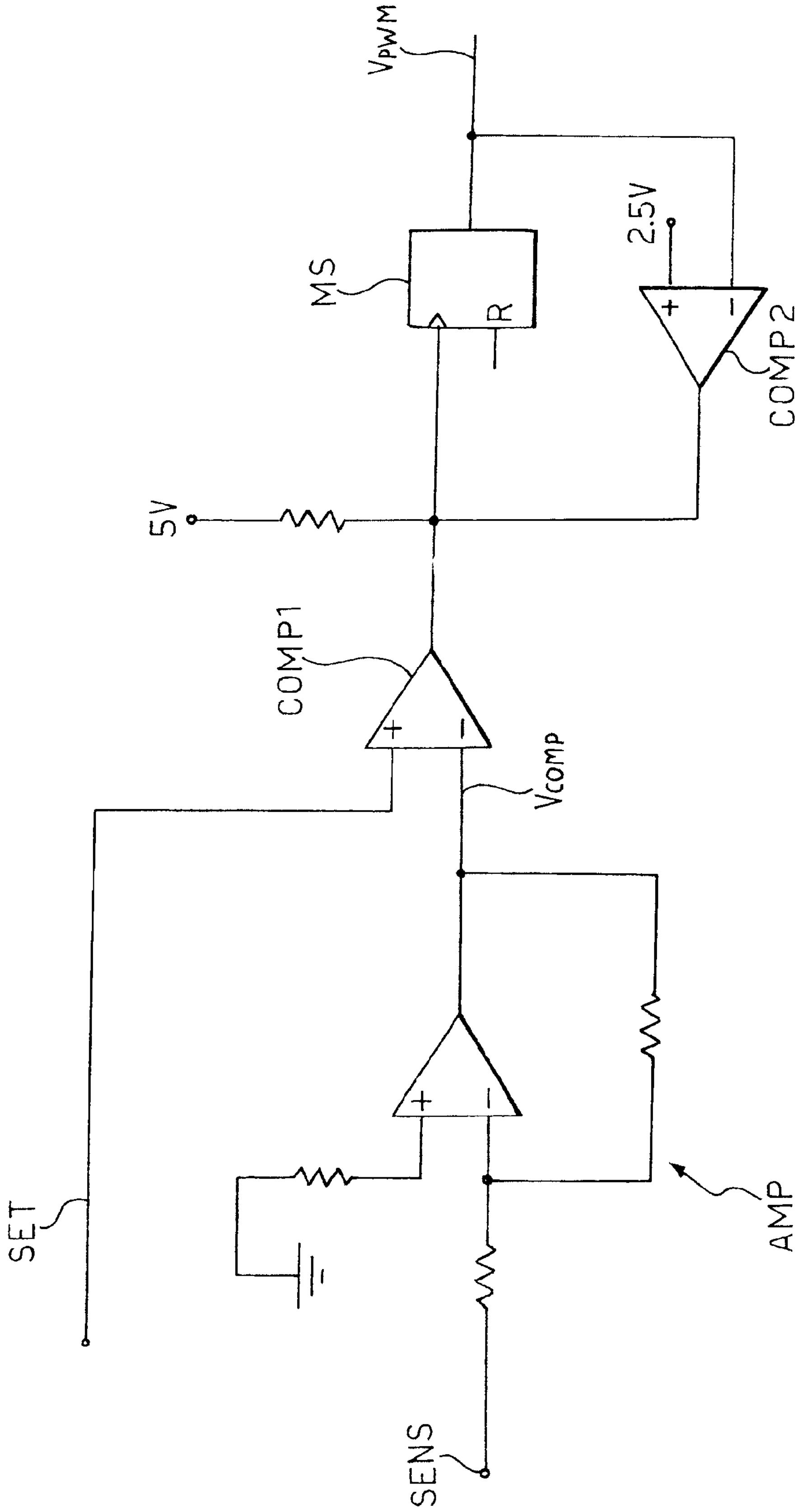
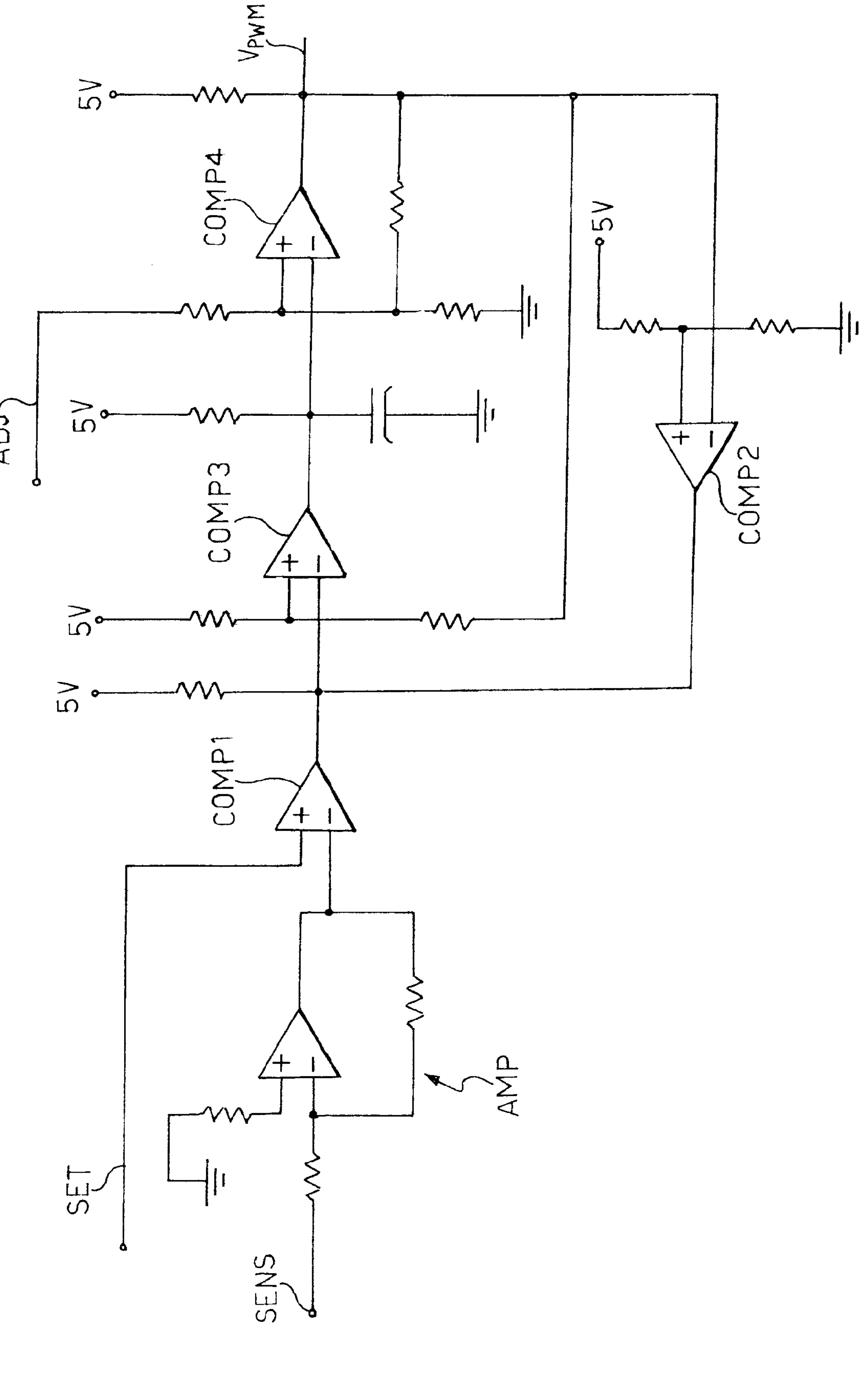


FIG.5



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EUROPEAN SEARCH REPORT

Application Number
EP 05 11 0774

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 1 381 060 A (SANKEN ELECTRIC CO., LTD) 14 January 2004 (2004-01-14)	1	H01F7/18
Y	* paragraph [0002] * * paragraph [0020] - paragraph [0028] * * paragraph [0041]; figures 1,4 * -----	2-8	
X	US 4 680 667 A (PETRIE ET AL) 14 July 1987 (1987-07-14)	9,10	
Y	* column 3, line 49 - column 5, line 38; figures 2,3 * -----	2-8	

TECHNICAL FIELDS SEARCHED (IPC)
H01F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	21 February 2006	Marti Almeda, R

CATEGORY OF CITED DOCUMENTS

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1

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 05 11 0774

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
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21-02-2006

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