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(71) Applicant: **AGENCE SPATIALE EUROPEENNE** [FR/FR]; 8-10 rue Mario-Nikis, 75738 PARIS CEDEX 15, France (FR).

(72) Inventors: **DELEPAUT, Christophe**; Krab 2, NL-2221 KW KATWIJK (NL). **LE GALLOU, Nicolas**; Willem Versteeghstraat 17, NL-2171 RB SASSENHEIM (NL).

(74) Agent: **REBOUSSIN, Yohann**; Cabinet Orès, 36 rue de St Pétersbourg, F-75008 Paris (FR).

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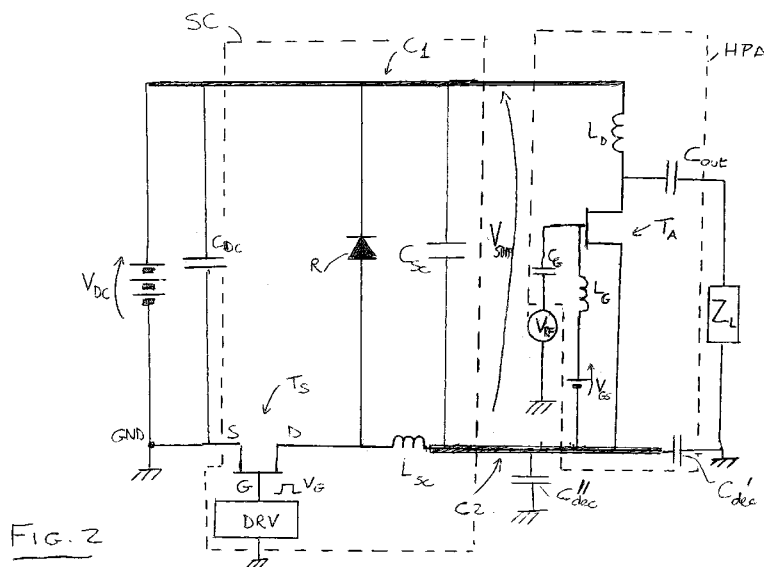
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(54) Title: RADIO-FREQUENCY HIGH POWER AMPLIFIER WITH BROADBAND ENVELOPE TRACKING BY MEANS OF REVERSED BUCK CONVERTER



(57) Abstract: A radio-frequency power amplifier with envelope tracking, comprising a power RF amplifying device (TA) for amplifying a RF signal and a switching DC/DC converter (SC) for providing said power RF amplifying device with a DC power supply at a voltage level (VSUPP) proportional to an envelope (VE) of said RF signal (VRF); characterized in that said switching DC/DC converter has a reversed buck topology. Advantageously said switching device is a N-type GaN Field Effect Transistor having its drain connected to the ground.

RADIO-FREQUENCY HIGH POWER AMPLIFIER WITH BROADBAND ENVELOPE TRACKING BY MEANS OF REVERSED BUCK CONVERTER

The invention relates to a radio-frequency power amplifier with envelope tracking, in particular for use in space telecommunications. The invention can also be applied e.g. to mobile telecommunication systems.

Radio Frequency (RF) transmitters on board of spacecraft do not always run at maximum power level. When operated at reduced RF power, the consumption of a RF High Power Amplifier (HPA) can be significantly reduced by lowering the voltage of its power supply.

The current state-of-the-art power supply for HPAs is referred to as "flexible" and consists in powering amplifiers with discrete preselected DC voltages. See e.g.:

- Darbandi et al., "Flexible S-band SSPA for Space Application", NASA/ESA Conference on Adaptive Hardware and Systems, 2008; and

- C R Green et al., "High Efficiency 240W GaN SSPA Demonstrator for Space Applications" ESA-MoD GaN round Table, September 2010, ESTEC, The Netherlands.

The power supply level is not optimized at any time of the HPA operation and the power saving is therefore limited.

A more advanced approach, which is the subject of an intense research effort, is referred to as "envelope tracking". It consists in providing the HPA with a continuously variable DC voltage, following ("tracking") the envelope of the RF signal to be amplified. This solution works well when the envelope bandwidth is limited to a few hundreds of kHz up to some MHz – e.g. in the case of terrestrial mobile systems (e.g. base stations, mobile phones). However, space applications have large bandwidths (20-100MHz); therefore efficient envelope tracking requires a very fast DC/DC converter.

For achieving high efficiency, the DC/DC converter should be a switching converter, or chopper. Moreover, telecommunication satellites generally use a 100 V power bus and a HPA power supply at 25 – 50 V, which imposes the use of a step-down converter. In practice, the most suitable

topology is the "buck" one, and a RF field effect transistor (FET) has to be used as the switching element of the converter, due to its low parasitic capacitances. Moreover, the transistor has to be of N-type, because high-frequency, high-voltage P-type transistors are not commercially available, and
5 in any case would have poor performances.

Using a N-type FET as the switching element of a buck converter, however, implies having its source alternatively connected to the input voltage and to the ground, and therefore experiencing fast variations of its voltage level. This is not a serious problem as long as the input voltage
10 does not exceed a few volts, which allows directly driving the floating gate of the transistor. So, very high-frequency DC/DC converters using both GaAs Depletion and Enhanced mode transistors have been disclosed, see e.g.:

- V. Pala et al., "Integrated High-Frequency Power Converters Based on GaAs pHEMT: Technology Characterization and Design
15 Examples", IEEE Transactions on Power Electronics, May 2012;

- V. Pala et al., "Application of GaAs pHEMT Technology for Efficient High Frequency Switching Regulators", Proceedings of The 22nd International Symposium on Power Semiconductor Devices & ICs, Hiroshima, 2010; and

- E. Busking et al., "1 GHz GaAs Buck Converter for High
20 Power Amplifier Modulation Applications", European Microwave Integrated Circuits Conference, Amsterdam, October 2012.

At higher voltage levels, however, the floating gate has to be driven through an isolation transformer. But then, at very high switching
25 frequency, the parasitic capacitance between transformer coils will lead peak current during switching whose amplitudes become incompatible with proper converter operation.

This problem would not arise with P-type transistors. However, RF transistors capable of handling voltages of several tens or volts
30 or more (Silicon, GaAs or GaN technology) are only available in N-type.

A possible solution to avoid this difficulty consists in using a switching converter driven at a significantly lower frequency for tracking a low-

pass filtered version of the envelope. See e.g. EP 2 432 118. Clearly, this results in a reduced efficiency.

Other alternative solutions have been proposed

- Implementing multisource power supply with fast discrete
5 commutation between each DC voltage to follow the envelope variations. See e.g. FR2799063 and S. Forestier et al., "Development of a new dynamic bias control system to increase the power added efficiency and the linearity of a power amplifier for M-QAM modulation", ESA Microwave Workshop on Microwave techniques and technologies, 2005, ESTEC, The Netherlands.
- 10 - Using a power converter operated at reduced switching frequency, ensures the envelope tracking up to a given upper frequency, in combination with high bandwidth linear regulator. See e.g. J. Jeong et al., "High-Efficiency WCDMA Envelope Tracking Base-Station Amplifier Implemented With GaAs HVHBTs", IEEE Journal of Solid-State Circuits, Vol.
15 44, N° 10, October 2009 or M. Hassan et al., "A Wideband CMOS/GaAs HBT Envelope Tracking Power Amplifier for 4G LTE Mobile Terminal Applications", IEEE Transactions on Microwave Theory and Techniques, Vol. 60, N° 5, May 2012.
- Using larger number of converters (e.g. 10) operated at
20 proportionally lower switching frequency. See e.g. J. Strydom, "eGaN FET-Silicon Power Shoot-Out Volume 8: Envelope Tracking", Power Electronics Technology, May 2012 or Mark Norris et al, "10 MHz Large Signal Bandwidth, 95% Efficient Power Supply for 3G-4G Cell Phone Base Stations", Twenty-Seventh Annual IEEE on Applied Power Electronics Conference and
25 Exposition (APEC), 2012.

However they all lead to complex and expensive systems, with a much lower efficiency than that which could be achieved in principle using a simpler buck converter.

Radio-frequency amplifiers with broadband envelope tracking
30 have been realized using a fast step-up DC/DC converter with "boost" topology. See:

- F. Leroy et al., "Experimental Demonstration of High Frequency Switching Converter for Envelope Tracking Power Amplifier Applications", 63rd International Astronautical Congress, Naples, Italy, October 2012

- 5 - N. Le Gallou et al., "Over 10MHz Bandwidth Envelope-Tracking DC/DC converter for Flexible High Power GaN Amplifiers", IEEE International Microwave Symposium 2011

Indeed, when a N-type transistor is used as the switching element of a boost converter, its source is connected to the ground, and
10 therefore no isolation transistor is required to drive its gate. However, this approach is only possible in applications having a bus voltage which is lower than the voltage of the power supply of the HPA. This can be the case in scientific spacecraft, but not in telecommunication satellites. Moreover, boost converters are notoriously difficult to control because they are non-minimum
15 phase.

The invention aims at solving the aforementioned drawbacks of the prior art.

According to the invention, the problem of performing broadband envelope tracking (which implies high switching frequencies,
20 typically of several MHz) at high voltage levels (tens of volts) is solved by resorting to an unconventional converter topology, called "reversed buck". Although known *per se*, this topology is generally considered unsuitable to use in power conditioning because its output voltage is not referenced to the ground. However, the present inventors have realized that this is not a
25 drawback in the specific application considered here, namely envelope tracking.

An object of the present invention is then a radio-frequency power amplifier with envelope tracking, comprising a power RF amplifying device for amplifying a RF signal and a switching DC/DC converter for
30 providing said power RF amplifying device with a DC power supply at a voltage level proportional to an envelope of said RF signal; characterized in that said switching DC/DC converter has a reversed buck topology.

According to particular embodiments of the invention:

- Said power RF amplifying device may be connected between a first conductor which, during operation, is maintained at a constant positive voltage with respect to a ground reference point, and a second conductor serving as a local voltage reference; and said switching DC/DC converter may be connected for setting the voltage level of said second conductor with respect to said ground reference point at a positive value which is lower than the voltage of said first conductor.
- Said switching DC/DC converter may comprise a switching device having a first terminal connected to said ground reference point and a second terminal connected to said second conductor through an inductor and to said first conductor through a rectifier, said rectifier being configured to allow current flow only from said switch to said first conductor; also comprising a filtering capacitor connected between said first conductor and said second conductor.
- Said switching device may be a N-type Field Effect Transistor, said first terminal being a source and said second terminal being a drain. Using a different switching device is not excluded, but generally less advantageous. In particular, said switching device may be a GaN transistor.
- The radio-frequency power amplifier may further comprise a DC blocking capacitor connected between an output port of said power RF amplifying device and a RF-load, and a second DC blocking capacitor connected between an external RF source and the RF transistor input (gate).
- The radio-frequency power amplifier may further comprise a decoupling capacitor connected between said second conductor and said ground reference point.
- The radio-frequency power amplifier may further comprise a driving circuit for driving said switching device with a Pulse Width Modulation (PWM) signal representative of an envelope of the RF signal to be amplified. Advantageously, said driving circuit may be configured for driving said switching device in such a way that the voltage difference between said first conductor and said second conductor is proportional to said envelope of said

RF signal. In particular, said PWM signal may have a frequency greater or equal to 20 MHz (allowing the tracking of a broadband envelope), for example greater or equal to 50 MHz, and the constant positive voltage of the first conductor may be greater or equal to 25 V, and preferably to 50 V or 100 V
5 (because, as discussed above, alternative solution exist for lower voltage levels).

Additional features and advantages of the present invention will become apparent from the subsequent description, taken in conjunction with the accompanying drawings, wherein:

- 10 - Figure 1 shows a radio-frequency power amplifier with envelope tracking comprising a conventional buck converter supplying a RF amplifier;
- Figure 2 shows a radio-frequency power amplifier with envelope tracking comprising a reversed buck converter supplying a RF
15 amplifier according to an embodiment of the present invention;
- Figures 3A to 3D illustrate the operation of the reversed buck converter of figure 2;
- Figure 4 illustrates a possible implementation of the conventional envelope-tracking RF power amplifier of figure 1;
- 20 - Figure 5 illustrates a possible implementation of the inventive envelope-tracking RF power amplifier of figure 2;
- Figure 6 shows a control scheme of the reversed buck converter of figure 2; and
- Figures 7A, 7B and 7C show the result of a numerical
25 simulation in both time and frequency domains of the envelope tracking converter of figure 2.

Figure 1 shows the electric scheme of an envelope tracking RF amplifier HPA driven by a conventional buck DC/DC converter (reference SC').

30 The RF amplifier HPA comprises a N-type Depletion mode or Enhanced mode GaN transistor T_A , having its drain connected to a first conductor C1 through an inductor L_D , its source directly connected to a

second conductor C2 and the gate biased at a voltage V_{GS} through an inductor L_G .

The RF signal to be amplified, V_{RF} , is applied to the gate of the transistor through a DC blocking capacitor C_G . The amplified signal is
5 extracted from the transistor drain through a blocking capacitor C_{out} to be applied to a load Z_L , e.g. an antenna.

The second conductor C2 is connected to the ground (GND) to serve as a reference voltage. The first conductor C1 is at a positive voltage V_{SUPP} whose value is set by the buck converter SC'.

10 The converter SC' comprises, in a conventional way, a switching device T_S selectively connecting and disconnecting the first conductor C1 to a DC power supply (battery in parallel to a filtering capacitor C_{DC}) at a voltage V_{DC} which is higher or equal to the maximum allowed value of V_{SUPP} . The converter also comprises an inductor L_{SC} connected between
15 the switching device T_S and the first conductor C1, a capacitor C_{SC} connected between the first and the second conductor and a rectifier (diode or, as disclosed in EP 2 432 118, transistor connected as a two-terminal device) having an anode connected to the second conductor (i.e. the ground) and a cathode connected between the switching device and the inductor.

20 The operation of this conventional buck converter is known in the art. See e.g. ST Application Note AN513/0393 "Topologies for switched mode power supplies".

As explained above, however, switching device T_S has to work at a very high frequency (e.g. 100 MHz) and at a quite high voltage level (e.g.
25 $V_{DC}=100V$, V_{SUPP} comprised between 8 and 50 V), which requires the use of a RF transistor, hence N-type, for switching. As it can be seen, this means that the source S of the transistor is floating between the ground (0 V) and the input voltage (V_{DC}), while the drain D is at a constant voltage V_{DC} . As a consequence, the gate G must also be floating. This implies the use of an
30 insulating transformer IST between the gate G and the driving circuit DRV which generates a pulse width modulation signal V_G for opening and closing the switch.

As mentioned above, however, at very high switching frequency the parasitic capacitance between transformer coils induces peak currents during switching, whose amplitudes can be incompatible with proper converter operation. For example, a 1 pF parasitic capacitance sinks a 1 A
5 current peak to switch from 0 V to 100 V in 1% of the switching period at 100 MHz. Such a current level is far above the level of current circulating in the drive circuitry.

Other known schemes for driving floating gates are even less suitable for use at high frequency/high voltage because they are more
10 complex, therefore showing higher losses and/or having higher parasitic capacitances. See e.g. International Rectifier Application Note AN-978 "HV Floating MOS-Gate Driver ICs".

Figure 2 shows the electric scheme of an envelope tracking RF amplifier driven by a "reversed buck" converter SC, according to the
15 invention.

As it can be seen, in the reversed buck converter the switching device T_S and the inductor L_{SC} are disposed between the second conductor C2 and the ground GND. When the switching device is implemented by a N-type transistor, its source S is connected to the ground
20 and it is the drain D which is floating, being connected to the second conductor C2 via the inductor L_{SC} . This allows the driving circuit DRV to be directly connected to the gate G of the transistor, without the need for a transformer. As a consequence the problem discussed above, due to the parasitic capacitance of the transformer, does not arise.

25 Figures 3A, 3C and 3D show that, when the switch T_S is closed (between time t_0 and time t_1) a linearly increasing electric current flows from the battery through C1 and C2 to power the HPA, the excess/deficit of current charging/discharging capacitor C_{SC} . The "positive" terminal of this capacitor is at a constant voltage $V_1 = V_{DC}$, while the "negative" terminal is at a
30 voltage V_2 slightly oscillating according to the charge/discharge cycle. At $t=t_2$, the switch opens. As illustrated on figure 3B, a linearly decreasing current keeps flowing through the inductor L_{SC} to continue powering the HPA, the

excess/deficit of current charging/discharging the capacitor C_{SC} . V_1 remains equal to V_{DC} while V_2 slightly oscillates according to the charge/discharge cycle. The average value of V_2 depends on the duty cycle $\tau=(t_1-t_0)/(t_2-t_0)$, and so does the supply voltage level of the amplifier, $V_{SUPP}=V_2-V_1=V_2(\tau)-V_{DC}$.

5 The reversed buck topology is known in the art of power electronics. See:

- P. Jacqmaer et al. "Accurately modelling of parasitics in power electronics circuits using an easy RLC-extraction method" IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 13-16 May 2012, pages 1441 – 1446; and
- 10 - On Semiconductor Application Note NCL30100-D "Fixed Off Time Switched Mode LED Driver Controller".

However, the reverse buck topology is usually not used for power conditioning because its output voltage is referenced to the input
15 voltage (V_{DC}) and not to the ground. In particular, in spacecrafts it is required that all the equipments are referenced to a common ground, which is not compatible with the use a reverse buck.

However, this feature is not a drawback in the application considered here because the blocking capacitors C_G and C_{out} isolate the RF
20 signal source and the RF load from the DC potential difference between the amplifier HPA and the rest of the payload. Moreover, one or more decoupling capacitors (C_{dec}' , C_{dec}'' on figure 2) are provided between the second conductor C2 and the ground. In the embodiment of figure 2, both decoupling capacitors C_{dec}' , C_{dec}'' are necessary because they allow grounding at different
25 physical locations. Moreover, C_{dec}' operates at radio-frequency, while C_{dec}'' is used to filter the current flowing through the passive capacitance of inductor L_{SC} , and operates at the switching frequency of the TS transistor. Therefore, the two capacitors are technologically different.

Figure 4 illustrates a physical implementation of a
30 conventional RF high-power amplifier, of the kind represented under the reference HPA on figure 1. The amplifier is mounted on a printed circuit board PCB having a back-side metallization BSM which is in direct contact with a

wide metal ground plane MGP constituting a reference physical ground to which the microstrip lines MSG and MSD, feeding the gate and drain of the amplifying transistor T_A , are referenced. The DC voltages V_{GS} and V_{SUPP} (the latter being generated by the switching converter SC', not represented on figure 4) are also referenced to the metal ground plane MGP through vias connecting the front face of the printed circuit board to the metalized back-side. The RF input signal is fed from the external source V_{RF} , referenced to the metal ground plane.

Figure 5 illustrates a physical implementation of a RF high-power amplifier according to an embodiment of the present invention, of the kind represented under the reference HPA on figure 2. Like in the case of figure 4, the amplifier is mounted on a printed circuit board PCB having a back-side metallization BSM. However, said metallization is separated from the metal ground plane MGP by an insulating layer IL, so as to constitute an "internal" ground reference (corresponding to the second conductor C2 of figure 2) floating with respect to the "external" ground reference MGP (which corresponds to the "GND" reference on figure 2). The internal and external ground references are connected together at radio-frequency by decoupling capacitors C'_{dec} . The decoupling capacitor C_{dec} is not represented because it is internal to the switching converter SC.

The source of the amplifying transistor T_A is connected to back-side metallization BSM (not visible on the figure) and the microstrip line MSG is referenced to it, while the input RF voltage V_{RF} is referenced to the external ground reference MGP, the necessary voltage shift being ensured by capacitor C_G . Similarly, the load Z_L is referenced to the external ground MGP while the microstrip line MSD is referenced to the local ground BSM, the necessary voltage shift being ensured by the output capacitor C_{out} . The DC voltages V_{GS} and V_{SUPP} (the latter being generated by the switching converter SC, not represented on figure 5) are also referenced to the local ground through vias connecting the front face of the printed circuit board to the metalized back-side BSM.

An advantageous feature of the invention is that buck converters can easily be controlled in closed loop, which is not the case for boost converters. Figure 6 shows a block diagram of a feedback control for the envelope tracking amplifier of figure 2. A high bandwidth differential amplifier DA built around an operational amplifier with a series RC feedback network extracts, integrates and amplifies the output voltage V_{SUPP} of the reverse Buck converter in order to perform Proportional-Integral (PI) regulation, and provides it to the a pulse-width modulation driver PWMD in charge of controlling the ON/OFF operation of the converter switch T_S .

On figure 7A, V_{env} , made of straight line segments, represents the envelope of the RF signal i.e. the reference signal for the control of the converter. The output of the buck converter SC, V_{SUPP} , features a limited amplitude ripple at the switching frequency and follows the reference signal quite well thanks to the control scheme. The V_S^F signal represents the converter output signal where the ripple has been eliminated by an additional filtering (represented by C''_{dec} on Fig. 2 but which can be of different topology).

Figures 7B and 7C show, respectively, the open loop gain and phase of the control system of figure 6. It can be seen that the phase response is reasonably flat up to about 30 MHz: this means that the envelope tracking will work as expected for envelope bandwidths up to 30 MHz.

The invention has been disclosed with reference to a specific technology (GaN transistors, or more generally N-type transistors) and a specific application (space telecommunications). However, the scope of the invention is more general and also applies to different technologies and applications. In particular, the switching transistor T_S can be either of the enhancement (normally off) type or of the depletion (normally on) type, and of GaAs or LDMOS technologies. Same applies to the RF transistor T_A .

CLAIMS

1. A radio-frequency power amplifier with envelope tracking, comprising a power RF amplifying device (T_A) for amplifying a RF signal and a
5 switching DC/DC converter (SC) for providing said power RF amplifying device with a DC power supply at a voltage level (V_{SUPP}) proportional to an envelope (V_E) of said RF signal (V_{RF}); characterized in that said switching DC/DC converter has a reversed buck topology.
- 10 2. A radio-frequency power amplifier according to claim 1, wherein said power RF amplifying device is connected between a first conductor ($C1$) which, during operation, is maintained at a constant positive voltage (V_{DC}) with respect to a ground reference point (GND), and a second conductor ($C2$, BSM) serving as a local voltage reference; and wherein said
15 switching DC/DC converter is connected for setting the voltage level of said second conductor with respect to said ground reference point at a positive value which is lower than the voltage of said first conductor.
- 20 3. A radio-frequency power amplifier according to any of the preceding claims, wherein said switching DC/DC converter comprises a switching device (T_S) having a first terminal (S) connected to said ground reference point (GND) and a second terminal (D) connected to said second conductor ($C2$, BSM) through an inductor (L_{SC}) and to said first conductor ($C1$) through a rectifier (R), said rectifier being configured to allow current flow only
25 from said switch to said first conductor; also comprising a filtering capacitor (C_{SC}) connected between said first conductor and said second conductor.
- 30 4. A radio-frequency power amplifier according to claim 3, wherein said switching device is a N-type Field Effect Transistor, said first terminal being a source and said second terminal being a drain.

5. A radio-frequency power amplifier according to claim 4, wherein said switching device is a GaN transistor.

6. A radio-frequency power amplifier according to any of the preceding claims, further comprising a first blocking capacitor (C_{out}) connected between an output port of said power RF amplifying device and a RF-load, and a second blocking capacitor (C_G) connected between an input port of said RF amplifying device and a RF input signal source.

7. A radio-frequency power amplifier according to any of the preceding claims, further comprising a decoupling capacitor (C'_{dec}) connected between said second conductor and said ground reference point.

8. A radio-frequency power amplifier according to any of the preceding claims, further comprising a driving circuit (DRV) for driving said switching device with a PWM signal (V_G) representative of the envelope of the RF signal to be amplified.

9. A radio-frequency power amplifier according to claim 8 wherein said driving circuit is configured for driving said switching device in such a way that the voltage difference between said first conductor and said second conductor is proportional to said envelope of said RF signal.

10. A radio-frequency power amplifier according to any of claims 8 or 9, wherein said PWM signal has a frequency greater or equal to 20 MHz, for example greater or equal to 50 MHz, and wherein said constant positive voltage of the first conductor is greater or equal to 25 V, preferably to 50 V and even more preferably to 100 V.

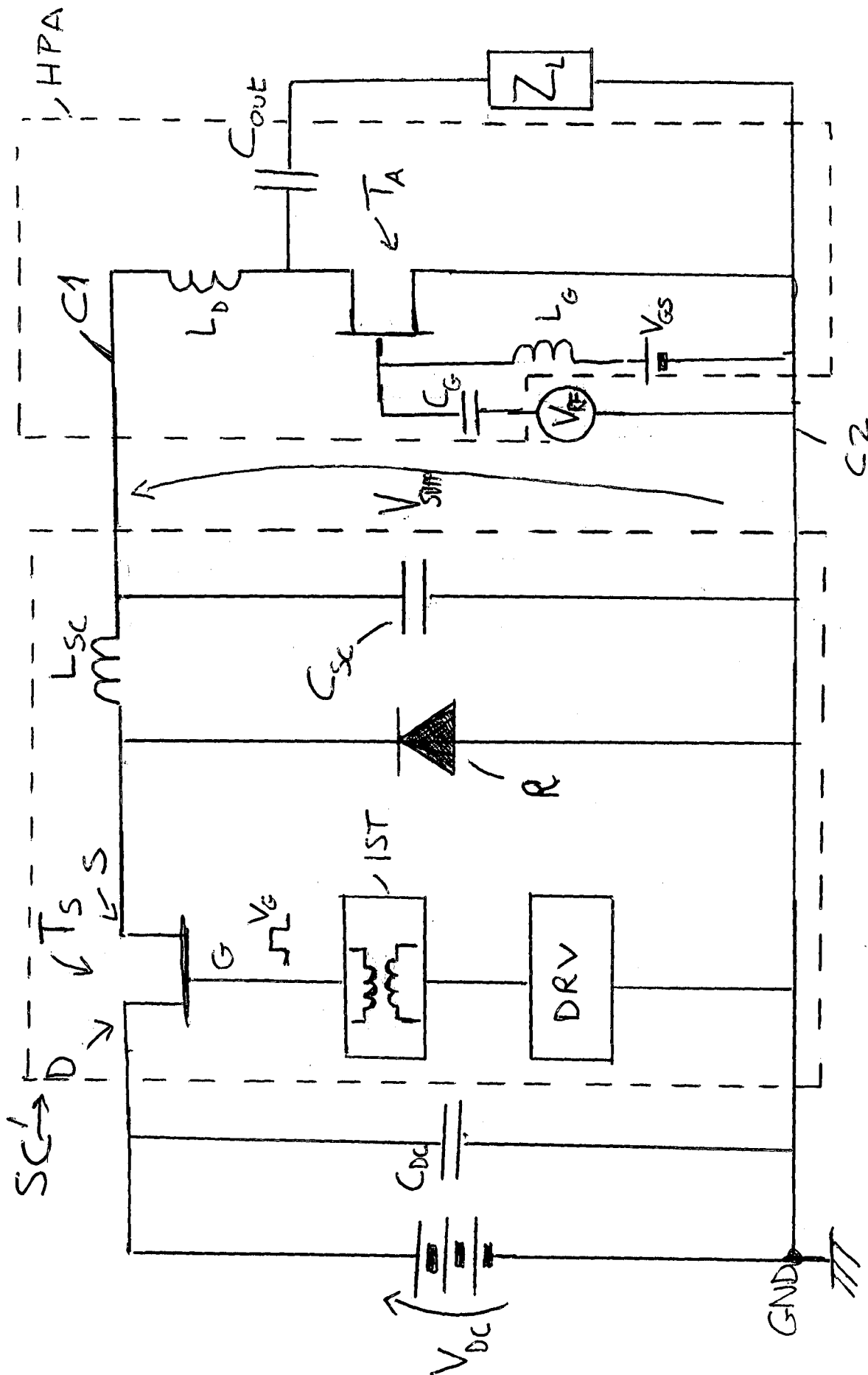
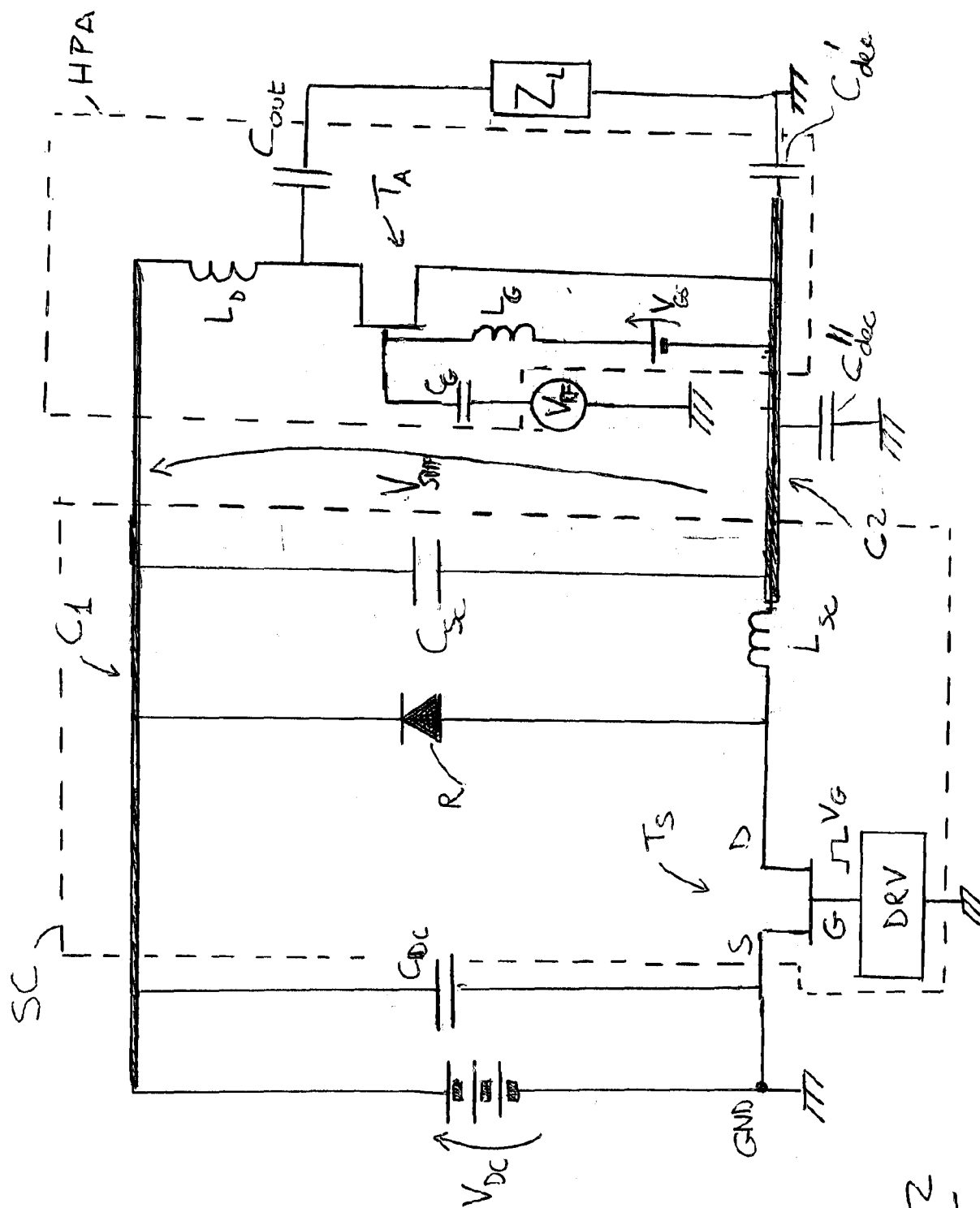


Fig. 1



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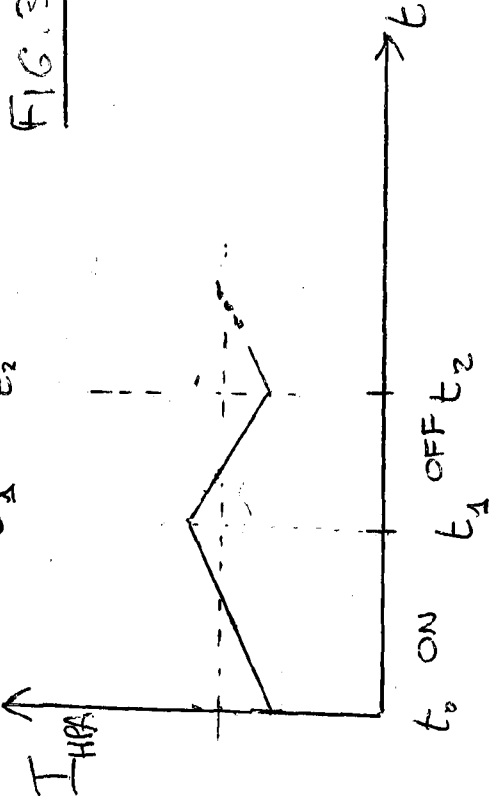
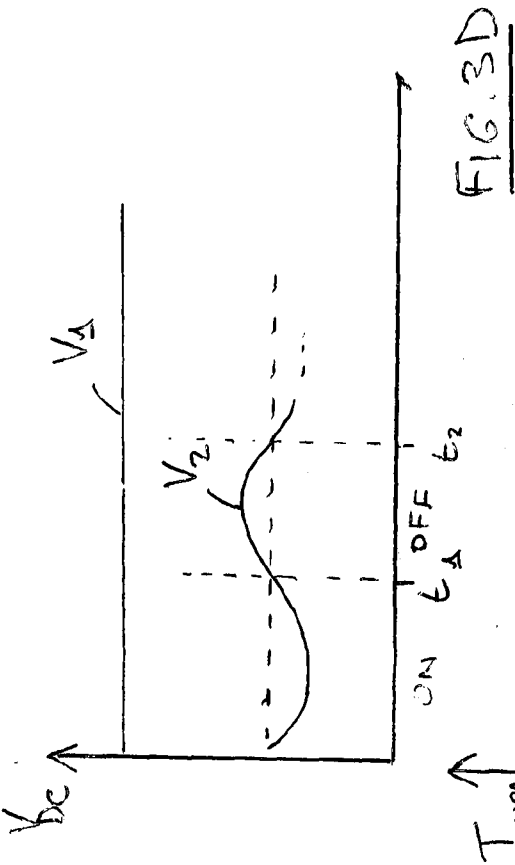


FIG. 3C

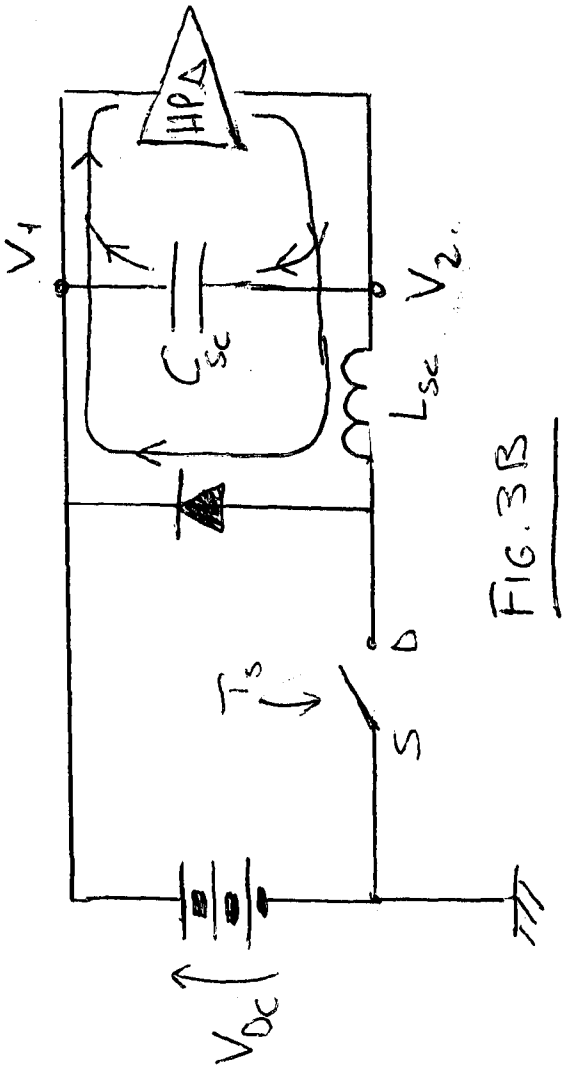


FIG. 3B

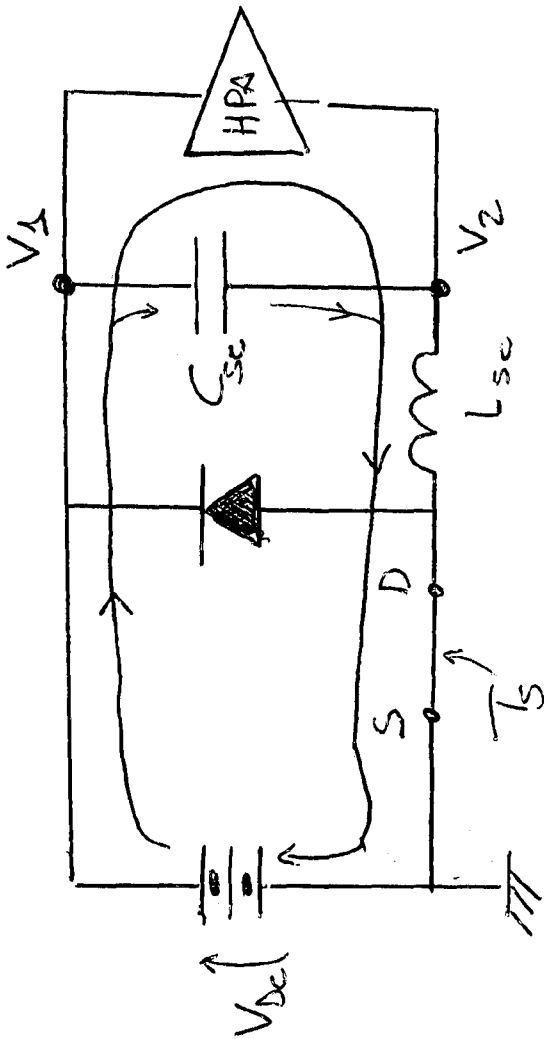


FIG. 3A

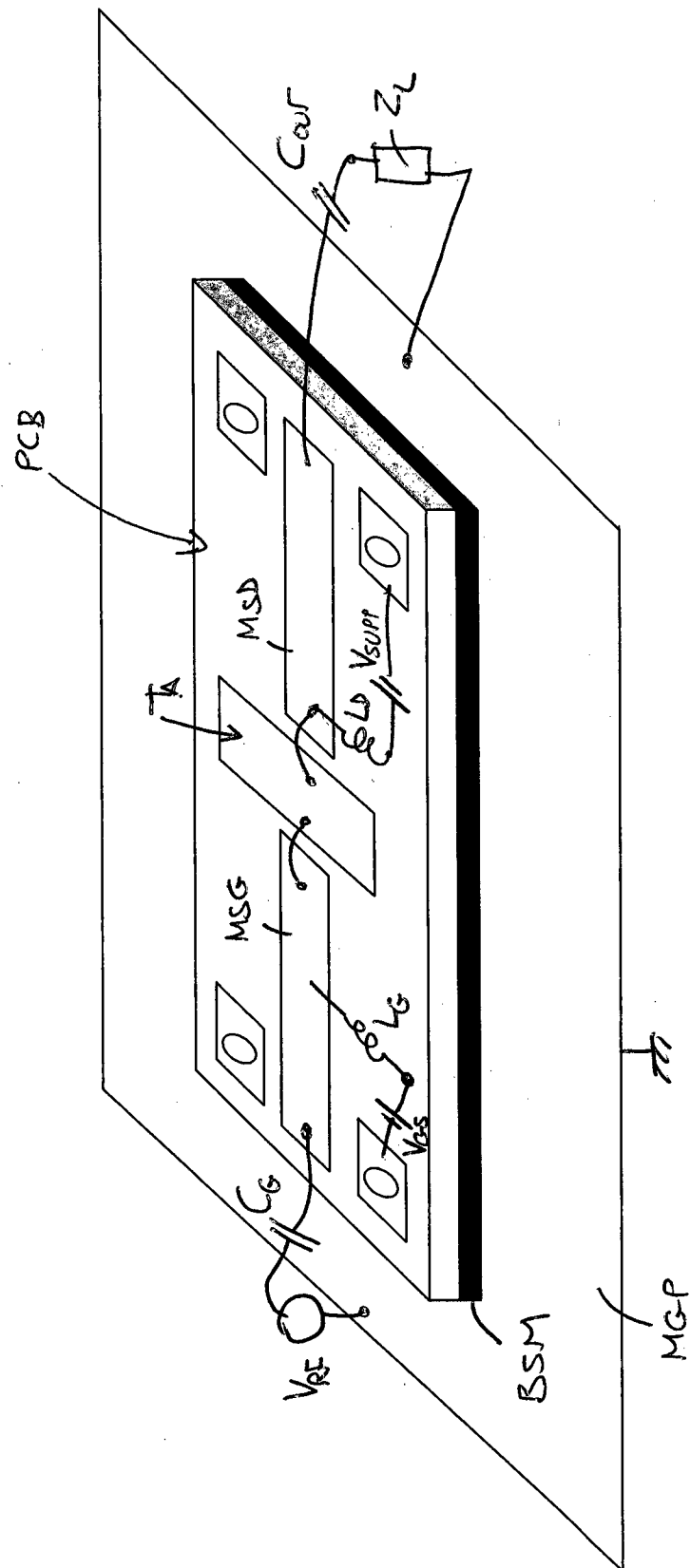


FIG. 4

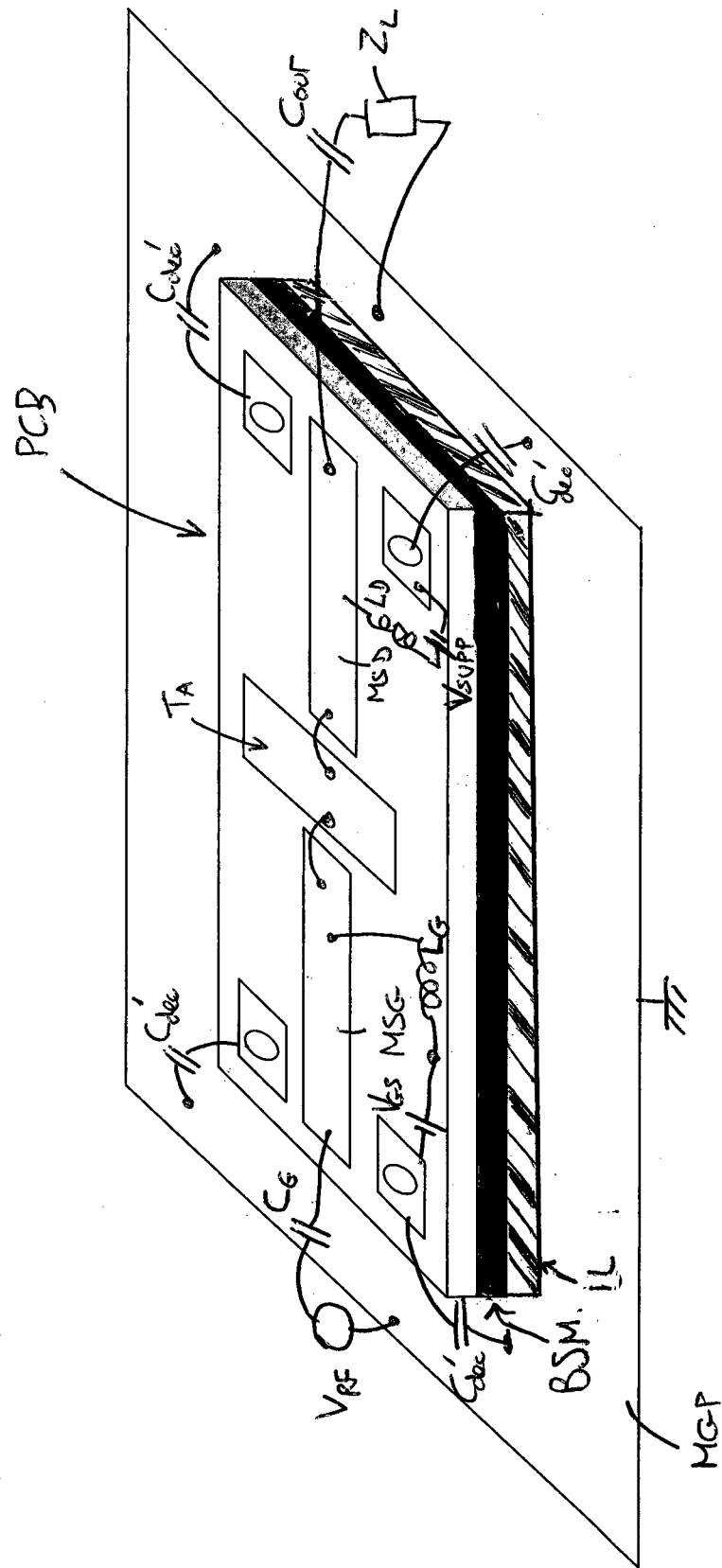


Fig. 5

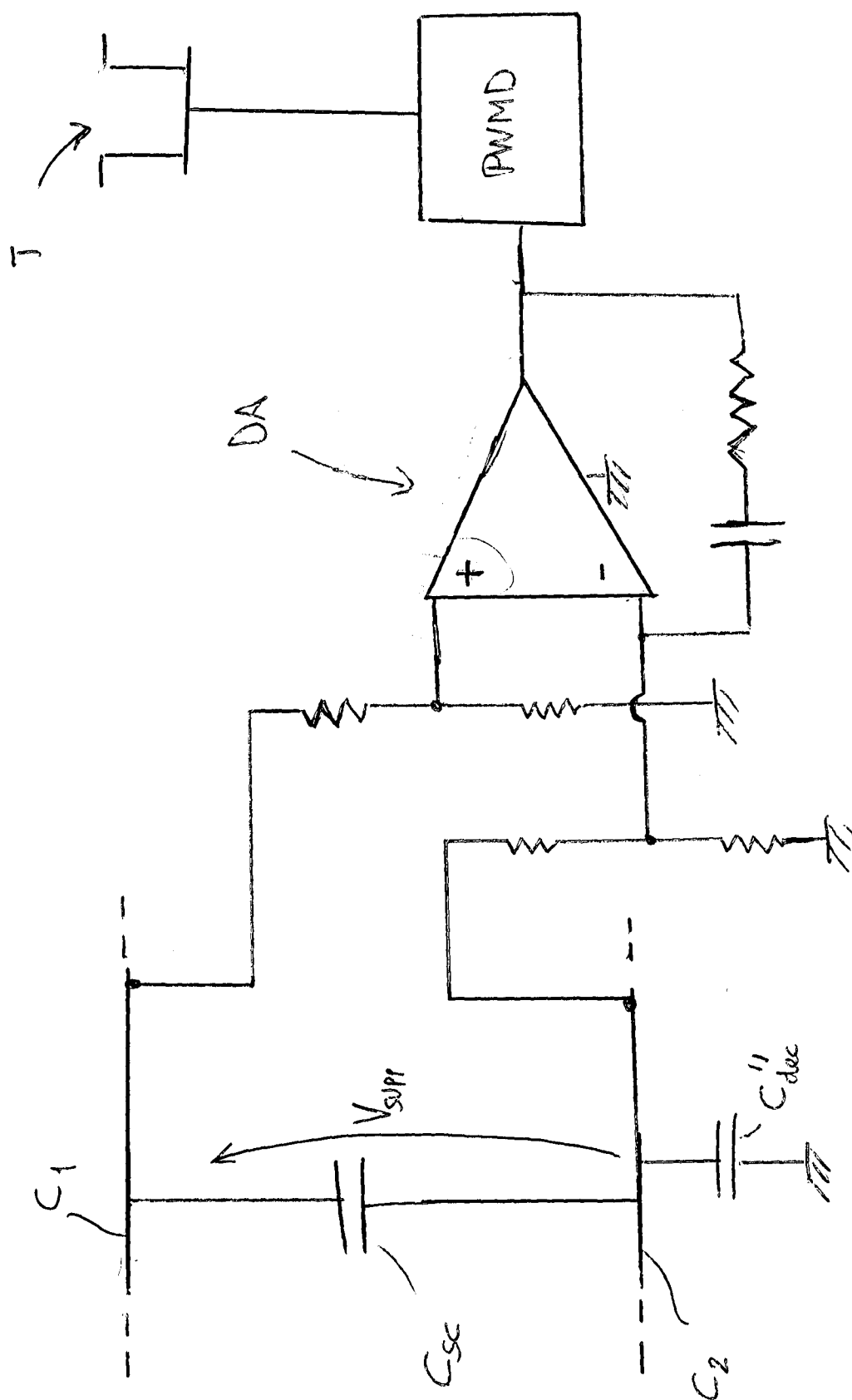


Fig. 6

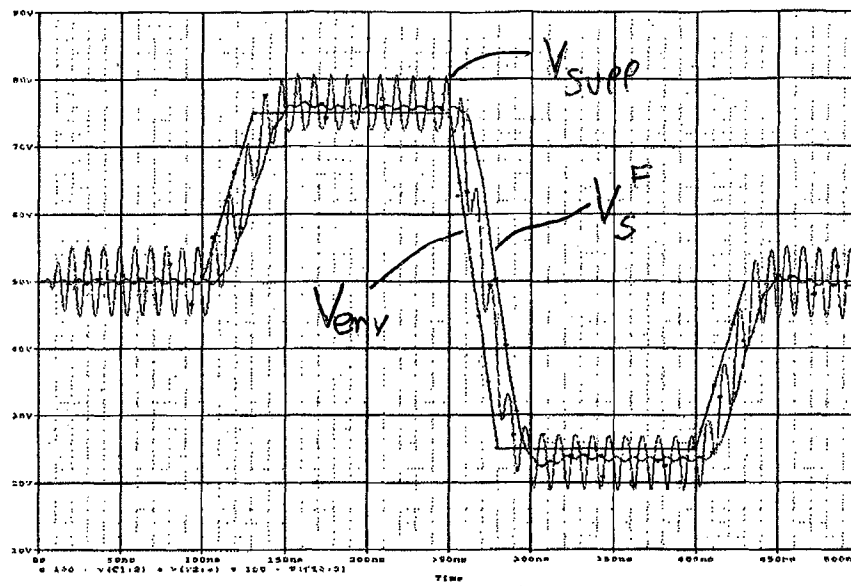


FIG. 7A

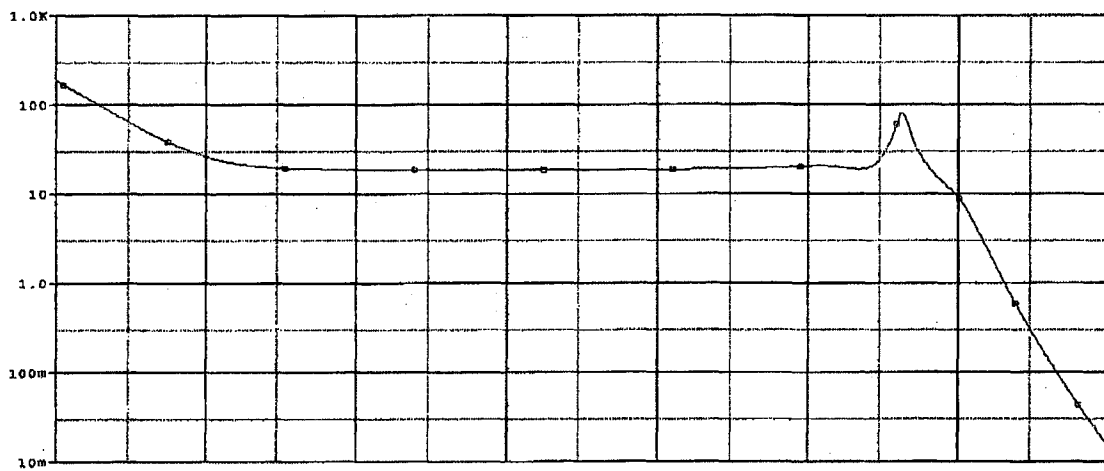


FIG. 7B

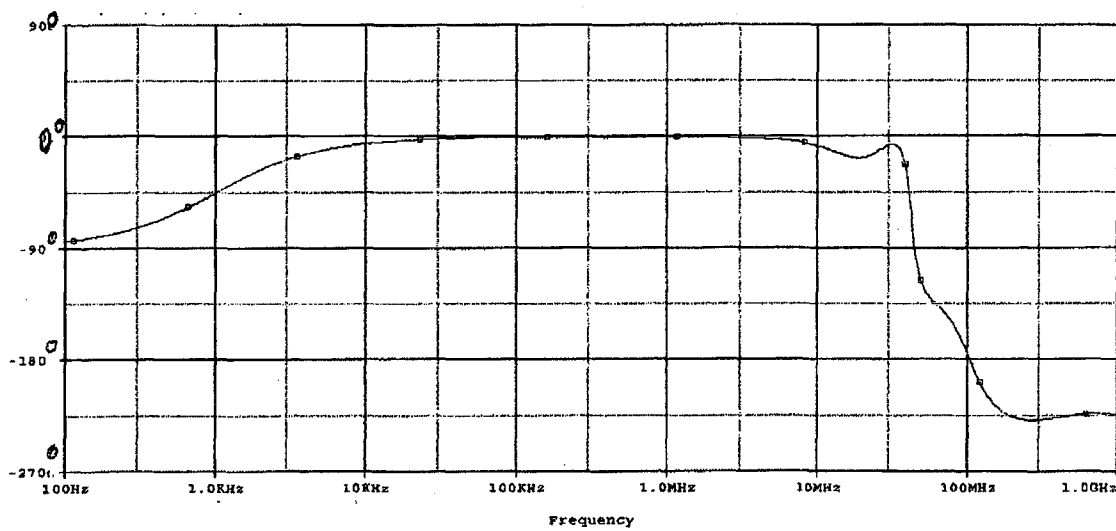


FIG. 7C

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/001041

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M3/158 H03F1/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H03F H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 432 118 A1 (EUROP AGENCE SPATIALE [FR]) 21 March 2012 (2012-03-21) cited in the application	1,4,5, 8-10
Y	figures 5,9B	2,3
A	paragraphs [0004], [0006], [0009], [0012], [0015], [0022], [0023], [0032], [0037]	6,7
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Further documents are listed in the continuation of Box C.



See patent family annex.

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29 November 2013

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Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Information on patent family members

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