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(71) Applicant:
MOTOROLA SEMICONDUCTEURS S.A.
F-31023 Toulouse Cédex (FR)

(72) Inventor: **Oddoart, Ludovic**
31270 Frouzins (FR)

(74) Representative:
Joly, Jean-Jacques et al
Cabinet Beau de Loménie
158, rue de l'Université
75340 Paris Cédex 07 (FR)

(54) Voltage regulator and method of regulating voltage

(57) A voltage regulator (100) for a power amplifier of a portable communications device, comprises an operational amplifier (110) and a power transistor (20) connected together so as to perform a voltage regulation function with the output (113) of the operational amplifier connected to a control terminal (21) of the power transistor (20), wherein the power transistor has an associated capacitance Cgs such that the initial biasing of the power transistor requires a start-up current to be supplied to its control terminal to charge the associated capacitance. The voltage regulator (100) additionally comprises start-up current generation means (200) having a current node (300) connected to the control terminal of the power transistor for supplying additional current to the control terminal of the power transistor during start-up of the regulator whereby the initial biasing of the power transistor (20) is aided by the start-up current generation means (200).

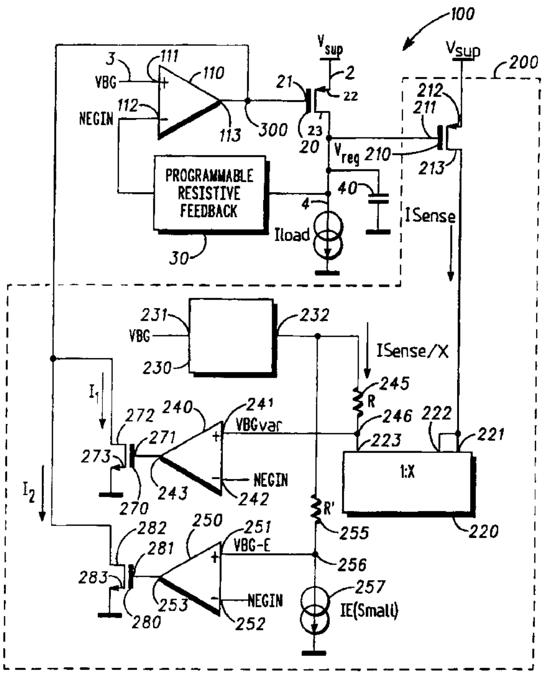

FIG. 2

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Description

Field of the Invention

[0001] The present invention relates to a voltage regulator and a method of regulating voltage, and in particular to a voltage regulator for a power amplifier of a portable communications device.

Background of the Invention

[0002] Voltage regulators for use with a power amplifier of a portable communications device such as a cellular telephone need to satisfy a number of important criteria. They must be able to generate the required output voltage quickly (i.e. they must have a short start-up time) without any significantly large overshoot. In addition, they must ideally be able to operate correctly when being supplied with a number of different supply voltages and when providing a number of different regulated output voltages.

[0003] Conventional voltage regulators achieve these criteria by providing an op-amp which is sufficiently large (in terms of the amount of current which it consumes) to turn on the voltage regulator quickly. The use of a large op-amp is advantageous because it provides a relatively robust and stable mechanism for quickly reaching the required output voltage; however, it is not well adapted for coping with varying start-up properties of the regulator as will be described below. Such circuits typically have problems with a small amount of overshooting where very fast rise times are involved. In order to avoid this problem of overshoot, an external RC circuit, whose values are chosen separately for each particular application, is connected to the gate of the power transistor or pass device of the regulator to ensure that adequate damping is achieved.

[0004] There is a further problem, in addition to the requirement of an external RC circuit, with a conventional regulator of this nature when used in the particular application of a portable communications device. In such a device, power must be used as sparingly as possible in order to prolong the period between recharging the device as much as possible. The further problem associated with the use of a relatively large operational amplifier is that it continues to consume a relatively large current for all of the time that the regulator is on, even though such a large current is only required by the op-amp during start-up of the regulator.

[0005] However, prior to the present invention, it was not deemed possible to use any alternative solution, because other solutions, it was generally perceived, would make the problem of overshoots worse, possibly to a degree beyond repair by an external RC circuit. This was particularly thought to be the case for voltage regulators employing an external MOSFET operating as the power transistor or pass device of the regulator (i.e. being located between the supply voltage and the output voltage of the regulator); most voltage regulators for use with portable communications devices now employ such transistors. The reason that external MOSFETs make the regulator particularly prone to overshoots is that the capacitance between the gate and source of the MOSFET (the gate-source capacitance, Cgs) varies with the voltage across the source and drain of the MOSFET (the drain-source voltage, Vds).

[0006] The amount of current which must be drawn away from the gate of the MOSFET in order to establish the correct voltage at the gate to generate the desired output voltage of the regulator varies with the gate-source capacitance Cgs and therefore also varies in dependence on the drain-source voltage, Vds. Since the regulator must be able to work with different supply voltages (e.g. different batteries, the output voltage of a switched mode power supply when the device is connected to a mains supply for charging, 12V when connected to a car battery supply, etc.), and ideally also with different output regulated voltages (for use in different devices for example), the regulator must be able to cater for the change in Cgs of the power MOSFET with different drain-source voltages (since the difference between the supply voltage and the output regulated voltage determines Vds). Furthermore, the relationship between Vds and Cgs is not even a straightforward linear relationship but a more complex inverse square relationship.

Summary of the Present Invention

[0007] According to a first aspect of the present invention, there is provided a voltage regulator for a power amplifier of a portable communications device, comprising an operational amplifier and a power transistor connected together so as to perform a voltage regulation function with the output of the operational amplifier connected to a control terminal of the power transistor, wherein the power transistor has an associated capacitance such that the initial biasing of the power transistor requires a start-up current to be supplied to its control terminal to charge the associated capacitance, and wherein the voltage regulator additionally comprises start-up current generation means having a current node connected to the control terminal of the power transistor for supplying additional current to the control terminal of the power transistor during start-up of the regulator whereby the initial biasing of the power transistor is aided by the start-up current generation means.

[0008] According to a second aspect of the present invention, there is provided a method of regulating voltage in a voltage regulator for a power amplifier of a portable communications device, the voltage regulator comprising an operational amplifier and a power transistor connected together so as to perform a voltage regulation function with the output of the operational amplifier connected to a control terminal of the power transistor, wherein the power transistor has an associated capacitance such that the initial biasing of the power transistor requires a start-up current to be supplied to its control terminal to charge the associated capacitance, the method comprising the steps of controlling the output voltage of the voltage regulator by supplying current to the control terminal of the power transistor, wherein the current is generated both by the op-amp and, during start-up of the regulator, by start-up current generation means having a current node connected to the control terminal of the power transistor for supplying additional current to the control terminal of the power transistor during start-up of the regulator whereby the initial biasing of the power transistor is aided by the start-up current generation means.

[0009] In a preferred embodiment of the present invention, the start-up current generation means includes measurement means for measuring a property indicative of the associated capacitance of the power transistor, whereby the associated capacitance of the power transistor may be determined. Preferably the start-up current generation means includes magnitude control means for varying the total amount of current supplied to the control terminal of the power transistor during start-up of the regulator in dependence upon the associated capacitance of the power transistor, whereby an appropriate current is supplied to the current node of the start-up current generation means for correctly biasing the power transistor during start-up of the regulator. Furthermore, the start-up current generation means preferably also includes current shaping means for shaping the current supplied to the control terminal of the power transistor such that the amount of current supplied by the start-up current generation means decays with time so as to minimise any overshoots. Preferably, the measurement means comprises means for measuring the voltage across the current terminals of the power transistor.

[0010] The power transistor is conveniently a P-channel Metal-Oxide Semiconductor Field Effect Transistor (P-MOSFET) having a gate (the control terminal) and a source and drain (the current terminals), there being a certain capacitance between the gate and the source (Cgs) which varies with the voltage applied across the drain and the source (Vds). In this case, the measurement means of the start-up current generation means preferably comprises a P-MOSFET sense-transistor whose gate and source are connected to the drain and source of the power transistor respectively. In this way, a sense current which flows through the sense-transistor approximately mirrors Cgs of the power transistor, such that a suitable current for biasing the power transistor may be generated from the sense current. Furthermore, when a P-MOSFET is used, the current required to initially bias the associated capacitance will be negative in the conventional sense. Clearly if an N-MOSFET were used instead the start-up current required would be positive in the conventional sense (it would not, however, be a sensible design choice to use an N-MOSFET because additional current consuming elements such as a charge pump would be required to make the regulator function correctly and adequately).

[0011] There are at least two significant advantages of a voltage regulator according to a preferred embodiment of the present invention. The first is that the average power consumption of the voltage regulator may be greatly reduced since the power consumption of the operational amplifier may be greatly reduced. The second advantage is that the amount of current required to correctly and quickly bias the power transistor with minimal overshoots is automatically generated without the requirement of an external RC circuit even where there are large variations in the supply voltage and/or the output regulated voltage.

Brief Description of the Figures

[0012] In order that the present invention may be better understood, an embodiment thereof will now be described by way of example only and with reference to the accompanying drawings in which:-

Figure 1 is a block diagram of the basic structure of a voltage regulator suitable for use with a power amplifier of a portable communications device;

Figure 2 is a block diagram of a voltage regulator according to the present invention;

Figure 3 is a graph illustrating the operation of the regulator of Figure 2 under a first set of initial conditions; and

Figure 4 is a graph similar to that of Figure 3 but illustrating the operation of the regulator of Figure 2 under a second set of initial conditions.

Detailed Description of the Invention

[0013] Referring to Figure 1 the basic structure of a voltage regulator 1 for a power amplifier of a portable communications device is seen to comprise an operational amplifier (op-amp) 10, a power transistor 20 operating as the pass device of the voltage regulator, programmable feed-back means 30 and a de-coupling capacitor 40.

[0014] The op-amp 10 has a non-inverting input 11, an inverting input 12 and an output 13. The power transistor 20, which in this case is a P-MOSFET, has a control terminal or gate 21, a first current terminal or source 22 and a second current terminal or drain 23. A supply voltage input 2 to the regulator 1 is connected to the source 22, and a regulated voltage output 4 of the regulator 1 is connected to the drain 23 of the power transistor 20. Additionally, the regulator has a reference voltage, VBG, input 3 connected to the non-inverting input 11 of the op-amp 10.

[0015] The output 13 of the op-amp 10 is connected to the gate 21 of the power transistor 20. The drain 23 of the power transistor 20 is connected to the inverting input 12 of the op-amp 10 via programmable feedback means 30; note that programmable feedback means 30 is simply a programmable voltage divider for outputting a divided down voltage from that input to it, the divisor value, B, being programmable. Such a programmable feedback means generally comprises a simple resistor ladder structure, one or more resistances of which may be bypassed or not by switching one or more bypass transistors on or off. Clearly by altering the ratio of resistances above and below the inverting input 12, the divisor B may be varied.

[0016] Decoupling capacitor 40 is connected between ground and the drain 23 of the power transistor 20.

[0017] When the regulator 1 is switched off, the output 13 of the op-amp 10 adopts a high impedance state and the capacitance Cgs between the gate 21 and source 22 is not charged resulting in a substantially zero biasing voltage Vgs between the gate and source of the power transistor 20, which in turn results in the transistor adopting an off state. In this state, decoupling capacitor 40 is also not charged and the voltage, Vreg, at the regulated voltage output 4 will be at ground regardless of the voltage, Vsup, applied to the supply voltage input 2 (note where, for example, Vsup is provided by one or more batteries, Vsup will be constantly applied to the Vsup input 2 of the regulator 1).

[0018] When the regulator 1 is turned on, operating current is supplied to the op-amp 10 which compares the voltages applied to its non-inverting and inverting inputs 11, 12, and attempts to produce at its output a voltage given by the difference between these input voltages multiplied by the gain of the amplifier, which in the present case is a large negative value. Since the voltage at the output 4 of the regulator 1 is initially substantially at ground, the voltage at input 12 will be lower than the positive reference voltage VBG applied to input 11 and as a consequence the voltage at output 13 will also attempt to go down (note that unless the input voltages are very almost equal, the output of the op-amp will be saturated, i.e. it will simply attempt to adopt the maximum or minimum voltage available to it from its power supply).

[0019] The effect of the output 13 going low is to commence charging of the associated capacitance Cgs of transistor 10. However, the rate of charging is limited by the amount of current that the op-amp 20 is able to sink and this in turn depends upon the amount of operating current that is supplied to the op-amp. As the capacitance Cgs charges, the voltage at the gate decreases and therefore the power transistor 20 starts to turn on, enabling current flow through the transistor 20 and reducing the voltage drop thereacross. The decoupling capacitor will start to charge up and the voltage at the regulated voltage output 4 of the regulator will increase. When the regulated output voltage substantially equals the reference voltage VBG multiplied by the divisor, B, of the programmable feedback means 30, the inverting and non-inverting inputs 12, 11 will be substantially equal and the regulator will be in a state of equilibrium in which the regulated voltage output 4 of the regulator is at the desired value. At this point the regulator 1 may be described as being in an on state, and the power transistor 10 as being correctly biased.

[0020] Referring now to Figure 2, there is shown a voltage regulator 100 for a power amplifier of a portable communications device, according to a preferred embodiment of the present invention. The basic architecture of regulator 100 is the same as that of regulator 1 of Figure 1, except that regulator 100 includes start-up current generation means 200 which is described in greater detail below. The other significant difference between regulators 1 and 100 is that op-amp 110 of regulator 100 is a much smaller op-amp than op-amp 10 of regulator 1 in terms of the amount of power which it consumes when it is on. Op-amp 100 has a non-inverting input 111, an inverting input 112 and an output 113 connected in the same way as the corresponding elements of op-amp 10. Like references have been used to describe corresponding elements in regulators 1 and 100 of Figures 1 and 2.

[0021] The start-up current generation means 200 comprises a sense transistor 210 which in this case is shown as a P-MOSFET, a 1:X current mirror 220, first and second voltage generating resistors 245, 255, a band gap follower 230, first and second comparators 240, 250 and first and second start-up transistors 270, 280.

[0022] Sense transistor 210 has a source 212 connected to the source 22 of the power transistor 20, a gate 211 connected to the drain 23 of the power transistor 20 and a drain 213 connected to master input(s) 221, 222 of the current mirror 220. First voltage generating resistor 245 is connected between a slave output 223 of the current mirror 220 and the output 232 of the band gap follower circuit 230. The input 231 of the band gap follower circuit 230 is connected to the reference voltage VBG. The second voltage generating resistor 255 is connected between the output 232 of the band gap follower 230 and ground via a small current source 257. First and second start-up reference voltage nodes 246, 256 are located downstream of the first and second voltage generating resistors 245, 255 (i.e. the resistors are between the band gap follower 230 and their respective start-up reference nodes).

[0023] First and second comparators 240, 250 each have a non-inverting input 241, 251 connected to the first and second start-up reference voltage nodes 246, 256 respectively and an inverting input 242, 252, both of which are connected to the inverting input 112 of op-amp 110 so as to receive the same input voltage, NEGIN. Each output 243, 253 of the comparators is connected to the control terminal 271, 281 of the first and second start-up transistors 270, 280 respectively. The current electrodes 272,273; 282,283 of the start-up transistors are connected between a current node 300 and ground respectively. First and second start-up transistors 270, 280 have different physical characteristics (e.g. channel width and/or length) such that they will draw different currents from current node 300 even if the same bias voltage/current is supplied to their control electrodes. Current node 300 is connected to the control electrode of power transistor 20 (between the control electrode of the power transistor 20 and the output 113 of op-amp 110.

[0024] When it is desired to switch on regulator 100, operating power is supplied to op-amp 110, current mirror 220, band gap follower 230, comparators 240, 250 and current source 257 in order to switch these elements on. Thereafter, the basic regulator structure operates as normal to drive the output 113 of op-amp 110 low which attempts to bias the power transistor into the correctly biased conducting on-state. However, because op-amp 110 only consumes a small amount of power (and therefore effectively operates only as a low power comparator), it is not able to draw very much current away from the associated capacitance Cgs of the transistor. If it were not for the start-up current generation means 200, the operation of which is described below, this would lead to a very slow turn-on time of the regulator.

[0025] However, in addition to the operation of the basic regulator structure, the start-up current generation means 200 also operates as follows. Sense transistor 210 is on because of the voltage across its gate 211 and source 212, which corresponds to the voltage across the source and drain, Vds, of the power transistor (given by Vds=Vsup-Vreg). The current generated by the sense transistor is given by $Isense=k.(Ws/Ls).(Vsup\text{-}Vreg\text{-}Vt)^2$ where k is a constant, Ws and Ls are physical properties of the sense transistor and Vt is the threshold voltage of the sense transistor, and this is input to the master inputs 221, 222, etc. This causes a fraction of Isense (Isense/X where X is the ratio of the current mirror 220) to flow into the slave input of the current mirror. The effect of this current Isense/X flowing through resistor 245 is to generate a voltage VBGvar at first start-up reference voltage node 246 given by VBGvar=VBG-Isense.R/X where R is the resistance of resistor 245. In this way a voltage VBGvar is generated which varies according to the square of Vds across the power transistor. The smaller Vds is, the larger is the associated capacitance Cgs of the power transistor and the closer VBGvar will be to VBG.

[0026] In a similar manner, a voltage VBG-E is generated at the second start-up reference voltage node 256 given by VBG-E=VBG-IE.R' where IE is the current generated by the small current source and R' is the resistance of resistor 255. This small current IE through resistor 255 is used to create a small voltage offset E in order to avoid a second regulation loop once the output voltage of the regulator is established. The voltages VBGvar and VBG-E generated in this way are then compared by the first and second comparators respectively with NEGIN which is the voltage at the output of the feedback means 30.

[0027] As the regulator 100 turns on NEGIN will rise until it eventually reaches VBG. Since VBG-E is only a little lower than VBG, the second comparator 250 will be on for almost all of the start-up time until NEGIN has very almost reached its final value of VBG. The first comparator will remain on for a proportion of the start-up time which depends on how small Isense is.

[0028] While the comparators 240,250 are on they switch on start-up transistors 270,280 respectively, which in turn causes first and second start-up currents I_1 and I_2 to flow from the current node 300. The physical characteristics of the start-up transistors 270 and 280 are predetermined such that I_2 is a small value, while I_1 is a much larger value, the arrangement being such that in the worst case of the lowest anticipated value of Vds (corresponding to the largest value of Cgs) of the power transistor, the capacitance Cgs is correctly biased within an acceptably short period, in the knowledge that I_1 will be on for almost all of the start-up period. In other words, the desired magnitude of I_2 is calculated on the basis of the lowest anticipated value of Cgs, and then the appropriate size for transistor 280 is determined accordingly. Similarly, the desired magnitude of I_1 is calculated on the basis of the largest anticipated value of Cgs, and then the appropriate size for transistor 270 is set accordingly.

[0029] Figures 3 and 4 illustrate the start-up of regulator 100 under two extreme conditions of a large value of Vsup-Vreg and a low value of Vsup-Vreg respectively. It will be apparent from the above discussion and Figures 3 and 4 that the total current supplied to (or actually in this case drawn away from) the current node 300 in order to bias the power transistor 20 during start-up of the regulator depends upon the capacitance Cgs of the power transistor such that almost exactly the correct amount of current is drawn from the capacitance to ensure very quickly reaching the correct bias. Furthermore, the amount of current drawn is initially large but reduces as the correct bias is approached; this ensures that very little overshoot occurs which is particularly important where the power amplifier supplied by this voltage regulator is formed using Gallium Arsenide which is preferred for power amplifiers used in portable communications devices.

[0030] From the above discussion it will be apparent that the start-up current generation means 200 includes measurement means, in the form of sense transistor 210 for measuring a property indicative of the associated capacitance Cgs of the power transistor 20, whereby the associated capacitance of the power transistor may be determined and an appropriate current supplied to the current node 300 of the start-up current generation means 200 for correctly biasing the power transistor 20 during start-up of the regulator 100.

[0031] Once the regulator is correctly biased, the start-up current generation means is preferably switched off again by suitable means (not shown). However, even if the start-up current generation means 200 is left on while the regulator is on the total power consumed by all of the elements 220, 230, 240, 245, 250, 255, 257 will be small compared with the power consumed by the op-amp of conventional regulator 1 of Figure 1. This is because the majority of the start-up current in regulator 100 is provided by start-up transistors 270, 280 which are turned off after start-up of the regulator. The power controlled by these transistors during start-up is much more than the total power consumed by all of the other elements of the regulator 100.

Claims

1. A voltage regulator for a power amplifier of a portable communications device, comprising an operational amplifier (110) and a power transistor (20) connected together so as to perform a voltage regulation function with the output (113) of the operational amplifier (110) connected to a control terminal (21) of the power transistor (20), wherein the power transistor (20) has an associated capacitance such that the initial biasing of the power transistor (20) requires a start-up current to be supplied to its control terminal (21) to charge the associated capacitance, and wherein the voltage regulator (100) additionally comprises start-up current generation means (200) having a current node (300) connected to the control terminal (21) of the power transistor (20) for supplying additional current to the control terminal (21) of the power transistor (20) during start-up of the regulator whereby the initial biasing of the power transistor (20) is aided by the start-up current generation means (200).

2. A voltage regulator as claimed in claim 1, wherein the start-up current generation means (200) includes sensing means (210) for sensing a property indicative of the associated capacitance of the power transistor (20).

3. A voltage regulator as claimed in claim 2, wherein the sensing means (210) comprises a sense transistor arranged to generate a current whose value depends upon the voltage drop across the current terminals of the power transistor (20).

4. A voltage regulator as claimed in any one of the preceding claims, wherein the start-up current generation means (200) includes magnitude control means for varying the total amount of current supplied to the control terminal (21) of the power transistor (20) during start-up of the regulator in dependence upon the associated capacitance of the power transistor (20).

5. A voltage regulator as claimed in any one of the preceding claims, wherein the start-up current generation means (200) includes current shaping means for shaping the current supplied to the control terminal (21) of the power transistor (20) such that it decays with time.

6. A method of regulating voltage in a voltage regulator (100) for a power amplifier of a portable communications device, the voltage regulator (100) comprising an operational amplifier (110) and a power transistor (20) connected together so as to perform a voltage regulation function with the output (113) of the operational amplifier (110) connected to a control terminal (21) of the power transistor (20), wherein the power transistor (20) has an associated capacitance such that the initial biasing of the power transistor (20) requires a start-up current to be supplied to its control terminal (21) to charge the associated capacitance, the method comprising the steps of controlling the output voltage of the voltage regulator (100) by supplying current to the control terminal (21) of the power transistor (20), wherein the current is generated both by the operational amplifier (110) and, during start-up of the regulator, by start-up current generation means (200) having a current node (300) connected to the control terminal (21) of the power transistor (20) for supplying additional current to the control terminal (21) of the power transistor (20) during start-up of the regulator whereby the initial biasing of the power transistor (20) is aided by the start-up current generation means (200).

7. A method as claimed in claim 6, further comprising the step of sensing a property indicative of the associated capacitance of the power transistor (20).

8. A method as claimed in claim 7, wherein the step of sensing a property indicative of the associated capacitance of the power transistor (20) comprises generating a current whose value depends upon the voltage across the current terminals of the power transistor (20).

9. A method as claimed in any one of claims 6 to 8, wherein the total amount of current generated by the start-up current generation means (200) is varied in dependence upon the associated capacitance of the power transistor (20).

10. A method as claimed in any one of claims 6 to 9, wherein the current supplied to the control terminal (21) of the power transistor (20) is shaped such that it decays with time.

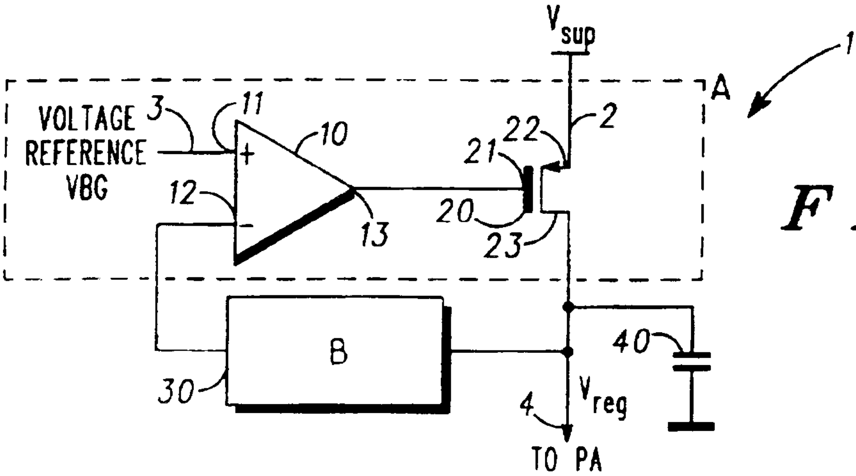
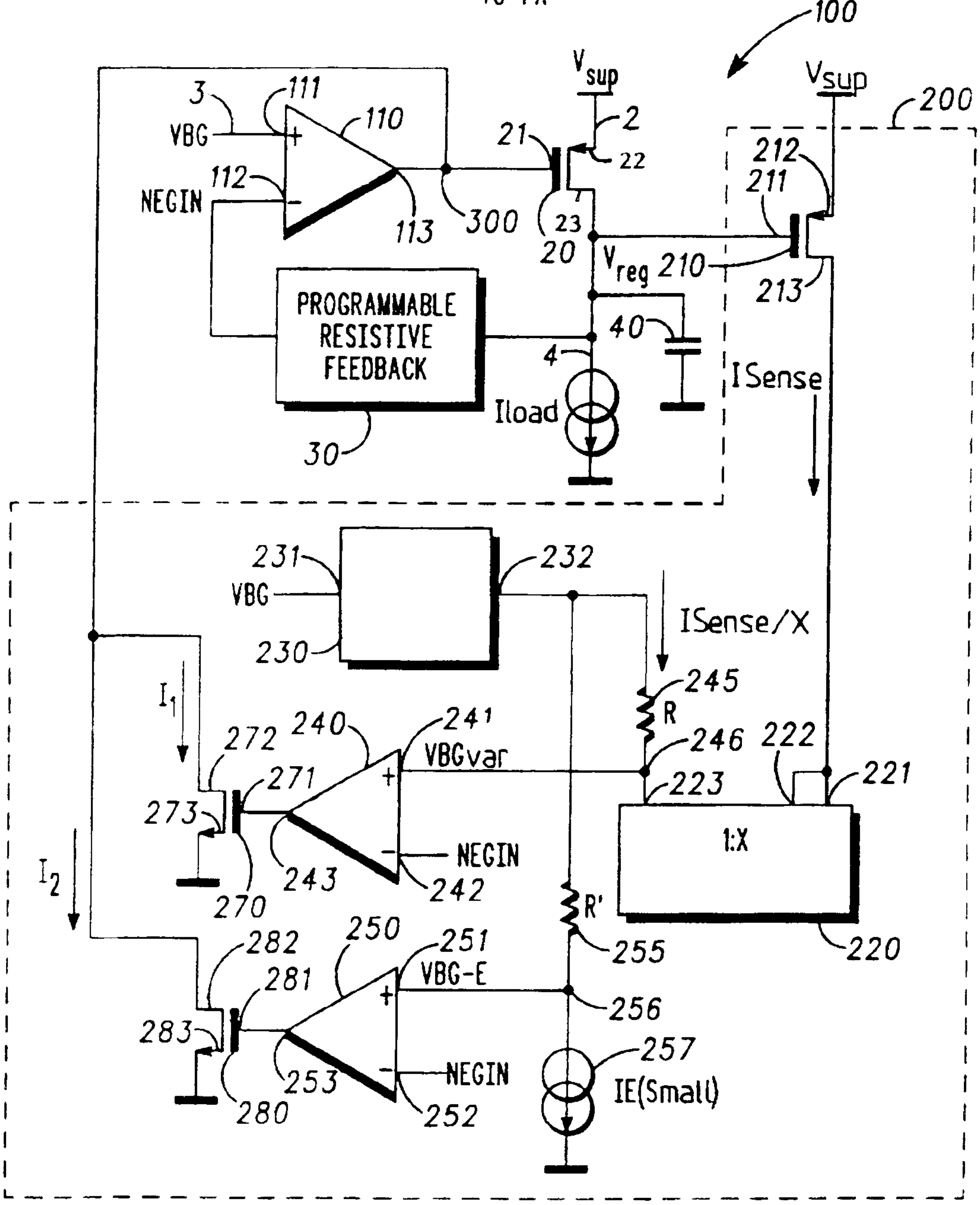

Vsup
1
A
VOLTAGE REFERENCE VBG
3
11
10
+
12
-
13
21
22
2
20
23
B
30
40
4
Vreg
TO PA

FIG.1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Vsup
Vsup
200
3
VBG
111
110
+
112
NEGIN
-
113
300
21
2
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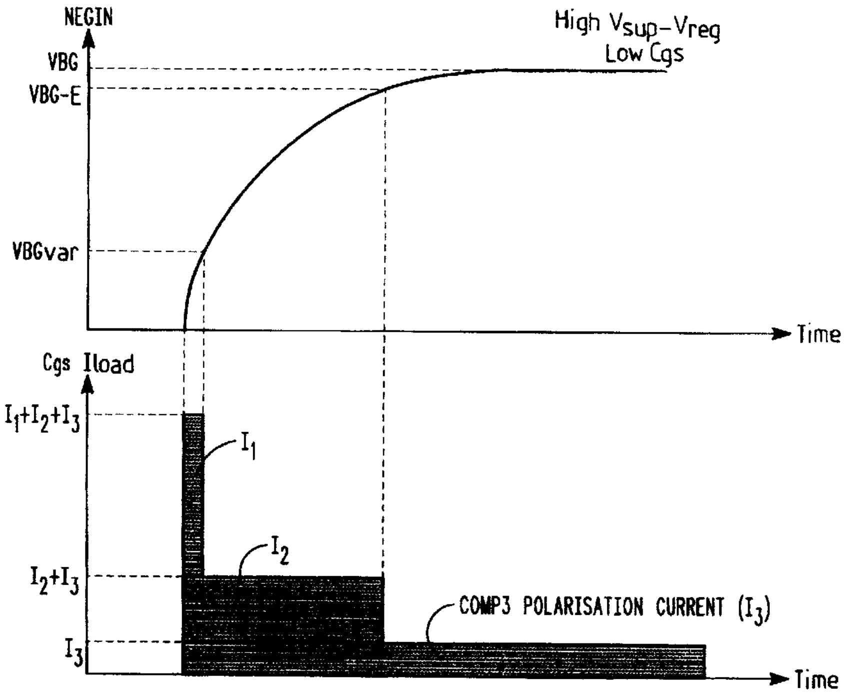
211
210
213
Vreg
PROGRAMMABLE RESISTIVE FEEDBACK
30
40
4
Iload
ISense
231
VBG
232
230
ISense/X
245
R
246
222
221
223
1:X
220
I1
272
240
241
VBGvar
271
273
243
NEGIN
242
270
I2
282
250
251
VBG-E
281
R'
255
256
283
253
NEGIN
252
280
257
IE(Small)

FIG.2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Low Cgs
VBG
VBG-E
VBGvar
Time
Cgs Iload
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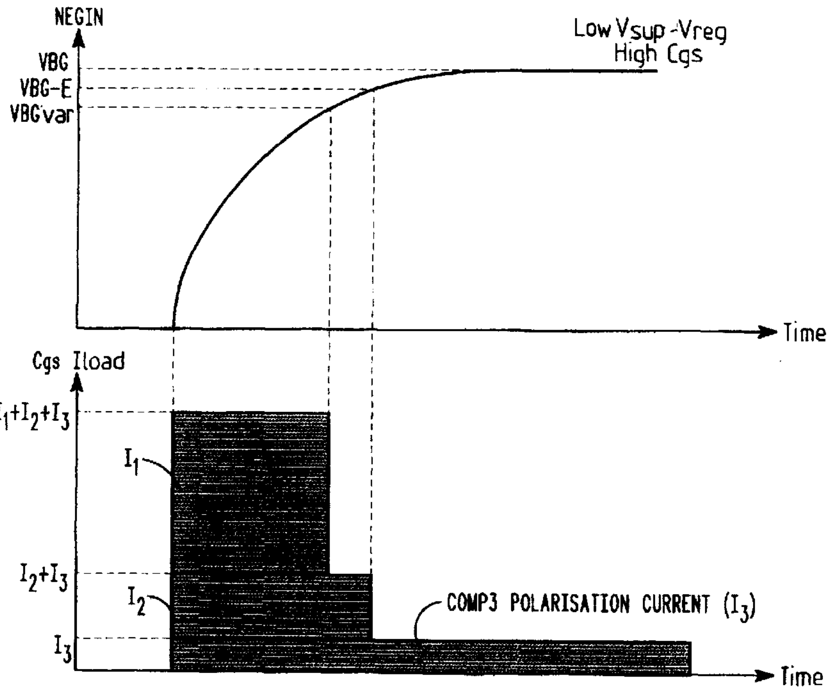
I1
I2
I2+I3
COMP3 POLARISATION CURRENT (I3)
I3
Time

FIG.3


NEGIN
Low Vsup -Vreg
High Cgs
VBG
VBG-E
VBG'var
Time
Cgs Iload
$I_1+I_2+I_3$
I_1
I_2+I_3
I_2
COMP3 POLARISATION CURRENT (I_3)
I_3
Time

F I G . 4

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EUROPEAN SEARCH REPORT

Application Number
EP 98 40 1714

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X	EP 0 731 553 A (SIEMENS AG) 11 September 1996	1,2,6,7	G05F1/575 G05F1/565
Y	* the whole document *	4,5,9,10	
X	EP 0 749 059 A (PHILIPS PATENTVERWALTUNG ;PHILIPS ELECTRONICS NV (NL)) 18 December 1996	1-6	
A	* the whole document *	2-5,7-10	
Y	KMETZ G L: "SOFT-START REGULATOR STARTS AT OV" EDN ELECTRICAL DESIGN NEWS, vol. 41, no. 12, 6 June 1996, page 104, 106 XP000622006	4,5,9,10	
A	* the whole document *	1-3,6-8	

TECHNICAL FIELDS SEARCHED (Int.Cl.6)
G05F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	12 November 1998	Schobert, D

CATEGORY OF CITED DOCUMENTS

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