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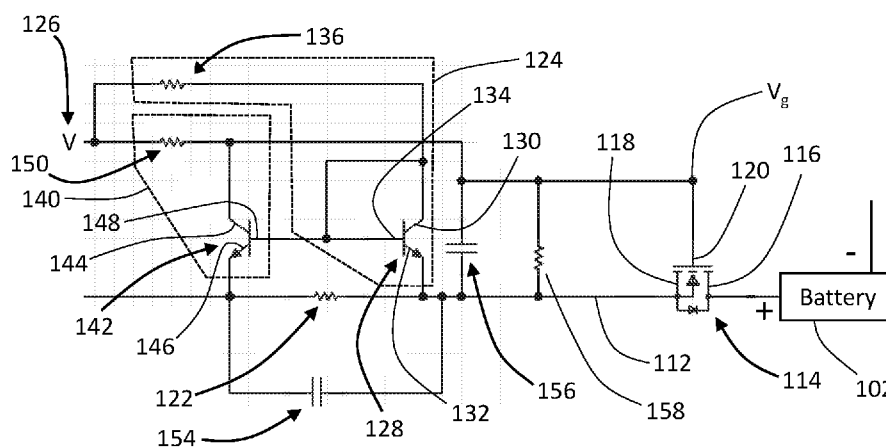


Figure 2

(57) Abstract: A circuit for limiting current includes a current modulating circuit comprising a current modulating circuit control terminal, a shunt resistance connected in series with the current modulating circuit, a current-to-voltage converter connected between a first input voltage and a first side of the shunt resistance, a voltage-to-current converter connected between a second input voltage and a second side of the shunt resistance opposite the first side of the shunt resistance. The current-to-voltage converter includes a first control terminal and a first primary current path through the current-to-voltage converter, the first primary current path comprising a first series resistance. The voltage-to-current converter comprises a second control terminal and a second primary current path through the current-to-voltage converter, the second primary current path comprising a second series resistance. The first and second control terminals are coupled to each other, and to the first primary current path and the control terminal of the current modulating circuit is coupled to receive a control signal from the first primary current path. Resistance values are selected such that an increase in voltage across the shunt resistance as current rises causes a reduction in current through the first primary current path, which in turn causes a change in the control signal such that current flow through the current modulating circuit is reduced.

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CIRCUIT FOR LIMITING CURRENT THROUGH A CONDUCTOR

TECHNICAL FIELD

The present invention relates to a circuit that controls an amount of current passing
5 through a conductor.

BACKGROUND

It can be desirable to control an amount of current flowing through a conductor. For
example, where the conductor supplies power to a circuit forming part of a device, there
10 may be practical or legal restrictions on a maximum amount of power that the circuit can
consume, or which a power supply can supply to the circuit.

One example of this is a battery-powered device, where it may be desirable, or even
compulsory, to prevent the device from consuming more than a certain amount of power
15 (15 W, for example) when the device is unattended.

SUMMARY

In a first aspect, the present invention provides a circuit for limiting current through a
conductor, the circuit comprising:

20 a current modulating circuit connected in series with the conductor, the current
modulating circuit comprising a current modulating circuit control terminal;

a shunt resistance connected in series with the current modulating circuit;

a current-to-voltage converter connected between a first input voltage and a first
side of the shunt resistance, the current-to-voltage converter comprising:

25 a first control terminal; and

a first primary current path through the current-to-voltage converter, the
first primary current path comprising a first series resistance;

a voltage-to-current converter connected between a second input voltage and a
second side of the shunt resistance opposite the first side of the shunt resistance, the
30 voltage-to-current converter comprising:

a second control terminal; and

a second primary current path through the current-to-voltage converter,
the second primary current path comprising a second series resistance;

wherein:

5 the first and second control terminals are coupled to each other, and to the first
primary current path;

 the current modulating circuit control terminal is coupled to receive a control
signal from the first primary current path; and

 wherein values of the first series resistance, second series resistance, and shunt
10 resistance are selected such that, as the current in the conductor increases, a corresponding
increase in voltage across the shunt resistance causes a reduction in current flow through
the first primary current path, which in turn causes a change in the control signal such
that current flow through the current modulating circuit is reduced.

15 Changing the control signal in this manner, in response to a decrease in current through
the first primary current path, facilitates the provision of a sensitive mechanism by which
current through the conductor can be controlled.

 The first input voltage and the second input voltage are optionally the same. This
20 simplifies the provision of power to the first and second primary current paths.

 Optionally, the values of the first series resistance, second series resistance, and shunt
resistance are selected such that a voltage at the current modulating circuit control
terminal approaches an operating threshold of the current modulating circuit for a voltage
25 drop across the shunt resistance of less than about 0.4 V, or more preferably less than
about 0.2 V, or more preferably less than or around 0.1 V.

 Optionally, the first series resistance is at least ten times the second series resistance, or
more preferably at least fifty times the second series resistance.

30

 The conductor may form part of a power supply circuit supplied by a battery.

The circuit may be configured to control current flow through the conductor such that the battery cannot supply more than 15 W to a further circuit for which the conductor forms part of a power supply circuit.

5

The current-to-voltage converter and the voltage-to-current converter may use the same type of transistor. Optionally, such transistors are gain-matched to within at least 70% of each other, or more preferably within 90% or 95%. For example, if BJTs are used, a minimum 70% match of at least hFE may be specified. Where greater accuracy and/or

10 predictability is desired, a 90% or 95% match of at least hFE may be specified.

Where other components, such as FETs, are used, such a minimum matching factor may include a gain factor.

15 Similar comments apply to a minimum match for temperature drift (i.e., when employed, a minimum 70% match may be sufficient, but a 90% or even 95% match may be chosen depending upon the implementation).

Where transistors are used in the current-to-voltage converter and the voltage-to-current

20 converter, connection of the first and second control terminals to the first current path may be made between the first series resistance and the transistor of the current-to-voltage converter

In a second aspect, there is provided an appliance comprising a circuit according to the

25 first aspect.

The appliance optionally comprises a battery, a terminal of the battery being coupled to the conductor.

The appliance may comprise high power circuitry for driving a motor and/or heating element, and low power circuitry including control circuitry for controlling the high power circuitry, the low power circuitry being powered by the conductor.

- 5 Features described above in connection with the first aspect of the invention are equally applicable to the second aspect of the invention, and vice versa.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic of an appliance comprising a current limiting circuit;

- 10 Figure 2 is a schematic of a current limiting circuit, optionally for use with the appliance of Figure 1;

Figure 3 is a simplified Ebers-Moll equivalent circuit for a bi-polar transistor;

Figure 4 is a schematic for simulating aspects of the current limiting circuit of Figure 2;

Figure 5 is a graph showing simulation results for the current limiting circuit of Figure 4;

- 15 Figure 6 is a schematic for simulating a circuit comprising the current limiting circuit of Figure 2;

Figure 7 is graph showing simulation results for the circuit of Figure 6;

Figure 8 is a graph showing calculation results for different resistance ratios ; and

Figures 9 and 10 are alternative implementations of current limiting circuits.

20

DETAILED DESCRIPTION

It may be desirable to control an amount of current or power that can be dissipated by a circuit. There may be practical limitations on the amount of power that can be safely provided by a power supply that powers such the circuit.

25

There may also be regulatory limits on the amount of power that certain types of circuit can consume or supply. For example, for safety reasons, some battery-based power sources may not be allowed to consume more than a certain amount of power (such as 15 W, for example) when unattended. One way of controlling power consumption is to limit

30 the amount of power that can be supplied to the circuit.

Figure 1 shows a battery-powered appliance 100. Appliance 100 can be, for example, a hair straightener, a vacuum cleaner, or other domestic appliance.

- 5 Appliance 100 is powered by a battery 102, which may take the form of, for example, a battery pack comprising a plurality of lithium ion cells (not shown).

Appliance 100 includes high power circuitry 104, which may include various different circuits and components, depending on the appliance type. For example, where appliance
10 100 is a hair straightener, high power circuitry 104 may include one or more heating elements and associated drive circuitry (not shown). Where appliance 100 is a vacuum cleaner, high power circuitry 104 may include one or more electric motors for generating suction and driving one or more brushes on a powered vacuum head, and associated drive circuitry (not shown). High power circuitry may be defined as, for example, circuitry that
15 consumes at least 20 W (and typically tens or even hundreds of watts) in operation.

Appliance 100 also includes low power circuitry 106 which includes a controller 108. Controller 108 includes one or more relatively low-power components, including, for example, a microcontroller (not shown). Controller 108 is coupled to control high power
20 circuitry 104, and may also be coupled to one or more sensors (not shown) for receiving signals relating to operating conditions of appliance 100. Such signals can be indicative of, for example, a battery state, a temperature of any heating elements, and other control and feedback signals. Controller 108 can also interface with, for example, battery charging circuitry (not shown) for controlling charging of battery 102.

25

Battery 102 is coupled to power both high power circuitry 104 and low power circuitry 106. A current limiting circuit 110 is coupled in series with a conductor 112 extending between the positive terminal of battery 102 and low power circuitry 106, to control the amount of current that can be supplied by battery 102 to low power circuitry 106.

30

For simplicity, minor implementation details of appliance 100 are omitted, including power supply and conversion circuits and a user interface through which the user can control the appliance and view settings, for example.

5 Figure 2 shows an example implementation of current limiting circuit 110. Current limiting circuit 110 comprises a current modulating circuit in the form of an N-channel MOSFET 114 connected in series with conductor 112. MOSFET 114 includes a drain 116, a source 118, and a current modulating circuit control terminal in the form of a gate 120. Drain 116 is coupled to the negative terminal of battery 102.

10

Current limiting circuit 110 includes a shunt resistance in the form of shunt resistor 122 coupled in series with MOSFET 114.

15 Current limiting circuit 110 includes a current-to-voltage converter 124 connected between a first input voltage and a first side of shunt resistance 122 (in this case, on the side of shunt resistance 122 closer to the negative terminal of battery 102). The first input voltage is a DC voltage 126 of 3.3 V, although the skilled person will appreciate that any other suitable voltage value or type may be used, depending upon the implementation.

20 Current-to-voltage converter 124 comprises a first transistor 128, which in the implementation of Figure 2 is an NPN bipolar junction transistor ('BJT') having a collector 130, an emitter 132 and a first base 134. First base 134 is a first control terminal of current-to-voltage converter 124. A first series resistance in the form of first resistor 136 is coupled in series with collector 130. Current-to-voltage converter 124 comprises a
25 first primary current path extending through first resistor 136, collector 130, and emitter 132.

30 Current limiting circuit 110 also includes a voltage-to-current converter 140 connected between a second input voltage and a second side of shunt resistance 122 opposite the first side of shunt resistance 122. In this case, the second input voltage is the same as the first input voltage, that is, DC voltage 126 of 3.3 V, although the skilled person will

appreciate that any other suitable voltage value or type may be used, depending upon the implementation.

5 Voltage-to-current converter 140 comprises a second transistor 142, which in the implementation of Figure 2 is an NPN bipolar junction transistor having a collector 144, an emitter 146, and a second base 148. Second base 148 is a second control terminal of voltage-to-current converter 140. A second series resistance in the form of a second resistor 150 is coupled in series with collector 144. Voltage-to-current converter 140 comprises a second primary current path extending through second resistor 150, collector
10 144, and emitter 146.

First base 134 and second base 146 are coupled to each other, and to first primary current path at collector 130 of first transistor 128, such that first transistor 128 is diode-connected.
15

Gate 120 of MOSFET 114 is coupled at collector 144 of second transistor 142 to receive a control signal from first primary current path, as described in more detail below.

A number of other illustrated circuit components perform incidental functions. For
20 example, a first capacitor 154 and a second capacitor 156 perform filtering/stabilising functions, while third resistor 158 performs a pulldown function, as will be understood by the skilled person. The situations in which such incidental circuit components may be desirable is well known to those skilled in the art, and so they will not be discussed further.

25 Values of the first resistor 136, second resistor 150, and shunt resistor 122 are selected such that, as the current in conductor 112 increases, a corresponding increase in voltage across shunt resistor 122 causes a reduction in current flow through the first primary current path, which in turn causes a change in the control signal such that current flow through the current modulating circuit is reduced. For example, in the implementation of
30 Figure 2, first resistor 136 has a value of 100 k Ω , second resistor 150 has a value of 1.5 k Ω , and shunt resistor 122 has a value of 0.1 Ω . However, any other suitable combination

of resistor values may be selected to suit the requirements of any particular implementation, as will be understood by the skilled person.

To explain the operation of current limiting circuit 110, it is useful to consider a large signal model based on an approximated Ebers-Moll transistor model. Figure 3 shows an approximated Ebers-Moll model applied to first transistor 128. The model approximates first transistor 128 as a current source 160 in series with a silicon diode 162 (i.e., forming part of the first primary current path), with first base 134 connected between current source 160 and diode 162.

As known by the skilled person, an approximation for the current flowing through the base-emitter junction can be derived from the silicon diode equation:

$$I_B = I_0(e^{\alpha V_{BE}} - 1), \quad 1$$

where I_0 is the diode dark current and:

$$\alpha = \frac{q}{k_B \cdot T} \quad 2$$

where q is the electron charge, k_B is the Boltzmann constant and T is the temperature in Kelvin.

The collector current can be approximated as:

$$I_c = g I_B \quad 3$$

where g is the BJT current gain (typically referred to as hFE in component datasheets).

Marking V_g as the gate voltage, V_a as the voltage 126, V_B as the common base voltage of first base 134 and second base 146, and assuming that first transistor 128 and second transistor 142 are identical, it can be concluded that:

$$\frac{I_{C1}}{I_{C2}} = \frac{e^{\alpha(V_B - V_s)} - 1}{e^{\alpha V_B} - 1} = \frac{V_a - V_g}{R_1} \cdot \frac{R_2}{V_a - V_B} \quad 4$$

Under typical operating conditions of $\alpha \sim 30 - 42$ (within typical temperature range), $V_B \sim 0.6 - 0.8$ and $V_a = 3.3V$, this further simplifies to:

$$V_g \approx V_a - e^{\alpha V_s} (V_a - V_B) \cdot \frac{R_2}{R_1} \quad 5$$

Based on the values of first resistor 136, second resistor 150, and shunt resistor 122 given above, the voltage across shunt resistor 122 required to reduce V_g to the point where MOSFET 114 is reaching its threshold and therefore limiting current through conductor 112 is around 0.1 V.

By way of comparison, if first transistor 128 were removed and the base of the second transistor connected to be controlled by the voltage across shunt resistor 122, the voltage across shunt resistor 122 required to cause MOSFET 114 to limit current through conductor 112 would be around 0.7 V at room temperature, and this voltage also varies with temperature. The skilled person will appreciate that this would result in a considerably higher energy consumption when current is being limited.

The analysis above assumes that first transistor 128 and second transistor 142 are identical. While a randomly selected pair of such components of the same type will rarely be identical, even if sourced from the same manufacturer, it is possible to bin components based on their measured properties.

It is also possible to specify “matched” components. Such components are generally manufactured on the same physical substrate, during the same manufacturing process, and are packaged with each other in the same physical package. Suppliers of such components typically provide a guaranteed degree of similarity across certain parameters, such as hFE and temperature drift.

It is desirable to use similar or matched components when implementing current-to-voltage converter 124 and voltage-to-current converter 140, since this ensures predictable circuit behaviour without the need for component testing or circuit calibration. The closeness with which the components must match can be selected to suit the particular implementation, but in the illustrated example using BJTs, a minimum 70% match of at least hFE may be sufficient in some implementations. Where greater accuracy and/or predictability is required, a 90% or even 95% match may be specified. Where other components, such as FETs, are selected, the minimum match may be based on their transconductance.

Similar comments apply to a minimum match for temperature drift (i.e., a minimum 70% match may be sufficient, but a 90% or even 95% match may be chosen depending upon the implementation).

Turning to Figure 4, there is shown a simplified version of the circuit shown in Figure 2, for the purpose of simulating circuit performance, in which components that correspond with those of Figure 2 are indicated with like reference signs. In Figure 4, the shunt resistor 122 of Figure 2 is replaced with a variable DC voltage source 164, a voltage of which is varied to simulate the shunt voltage across shunt resistor 122 for various current values through conductor 112. The voltage supplied to first resistor 136 and second resistor 150 is indicated by 3.3 V DC voltage source 126

Figure 5 shows a graph of gate voltage V_g against the varying shunt voltage generated by variable voltage source 164. Line 166 shows the relationship based on the large signal analysis of equation (5) above, and line 168 shows the relationship based on the circuit simulation shown in Figure 4. In both cases, the gate voltage falls relatively slowly as the shunt voltage increases towards 0.05 V. The rate at which the gate voltage falls accelerates, such that it falls below threshold voltage of MOSFET 114 at around 0.1 V for line 166 and 0.105 V for line 168.

Between 0.1 and 0.15 V, the gate voltage of both line 166 and line 168 has fallen sufficiently that the MOSFET 114 is no longer significantly conducting.

Figure 6 shows the circuit of Figure 4, in the context of simulating a particular current limiting application. Circuit 170 corresponds with the circuit of Figure 2. In addition, there is a load resistor 172, simulating a load such as a microprocessor and other low power circuitry as described above. A battery is simulated by a DC power supply 178. A switch 174 is controlled to simulate a short across load resistor 172. Switch 174 is controlled by a pulse generator 176, as described in more detail below. A capacitor 180 is connected in parallel with load resistor 172, and a 1 m Ω current-limiting resistor 182 is connected in series with power supply 178.

The values of the various components have been selected to limit current through conductor 112 to about 750 mA. To achieve this, the components of circuit 170 are as described above in relation to Figure 2. For example, load resistor 172 has a value of 30 Ω . The skilled person will appreciate that other component values may be selected to give the same, a similar, or a different current limit, in accordance with ordinary circuit design principles.

Capacitor 180 has a value of 150 μ F, for allowing simulation of current inrush when the circuit is initially supplied with power.

Figure 7 shows the simulated behaviour of the circuit of Figure 6. Initially, DC voltage 126 is at 0 V, and so MOSFET 114 remains turned off.

At $t = 20$ mSecs, DC voltage 126 is turned on (i.e., is switched from 0 V to 3.3 V). This causes voltage V_g to rise, which in turn causes MOSFET 114 to turn on.

While charging capacitor 180 via current-limiting resistor 182, the current I_t is limited to 750 mA by the operation of circuit 170 as described above. This can also be seen by the value of V_g being clamped just below 2 V.

Once capacitor 180 reaches full charge at around $t = 25$ mSecs, the current stabilises at a little below 750 mA. This simulates ordinary operation of the circuit as a whole. The skilled person will appreciate that the current consumption of the circuit during ordinary operation can be significantly lower than the clamped current, depending upon the implementation requirements.

At $t = 60$ mSecs, switch 174 is closed to simulate a dead short across load resistor 172. Both I_t and V_g initially spike, but are quickly controlled as circuit 170 operates to cause current clamping. Initially, the short caused by switch 174 closing increases current through MOSFET 114. This in turn causes a rise in the voltage across shunt resistor 122, which in turn causes the voltage at first base 134 and second base 146 to rise. This quickly causes second transistor 142 to turn on, which causes V_g to fall. Falling V_g reduces conduction of MOSFET 114, which in turn reduces current flow through shunt resistor 122.

This feedback loop quickly results in V_g stabilising at just below 2 V, which corresponds to the current through MOSFET 114 being clamped at around 750 mA.

Although the implementation illustrated in Figure 2 is configured to cause the current to start being clamped as the shunt voltage rises through around 0.1 V, the skilled person can modify the values of components, including first resistor 136, second resistor 150, and shunt resistor 122, such that a different shunt voltage initiates voltages clamping. Having a lower voltage threshold for the clamping allows for reduced energy consumption/supply when the current is being clamped. However, there are other factors that must be balanced against this, such as noise level, accuracy and maximum absolute gate voltage.

Figure 8, for example, shows example calculated curves for circuits having different ratios between first resistor 136 and second resistor 150. Curve 184 shows the gate voltage against shunt voltage for a second resistor 150 to first resistor 136 ratio of 0.01, curve 186

shows the gate voltage against shunt voltage for a second resistor 150 to first resistor 136 ratio of 0.025, curve 188 shows the gate voltage against shunt voltage for a second resistor 150 to first resistor 136 ratio of 0.05, and curve 190 shows the gate voltage against shunt voltage for a second resistor 150 to first resistor 136 ratio of 0.1.

5

In general, the first series resistance (e.g., first resistor 136) may be at least ten times the second series resistance (e.g. second resistor 150). The first series resistance is relatively high to reduce the amount of current flowing through the current-to-voltage converter, which in turn reduces energy consumption. The first series resistance may be at least fifty

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The values of the first series resistance, second series resistance, and shunt resistance may be selected such that a voltage at the current modulating circuit control terminal approaches an operating threshold of the current modulating circuit for a voltage drop across the shunt resistance of less than about 0.4 V. Optionally, this voltage may be less

15

Although acting as a current clamp, the circuit may be configured to control current flow through the conductor such that the battery cannot supply more than a particular total power to the further circuit for which the conductor forms part of a power supply circuit. For example, the circuit may be configured to control current flow through the conductor such that the total power during current clamping does not continuously exceed 15W. The skilled person will understand how to characterise the relationship between current and power consumption for the circuit for which the power is to be controlled, enabling a suitable clamping current to be selected.

20

25

Although appliance 100 is described as having high power circuitry 104 and low power circuitry 106, the skilled person will appreciate that other implementations may have only single (high- or low-power) circuit for which the current is controlled.

30

Other implementations may use different types of current-to-voltage and voltage-to-current converters. For example, Figure 9 shows an alternative version of the circuit of Figure 4, in which components that correspond with components in Figure 4 are indicated with like reference signs. The difference between the circuit of Figures 4 and 9 is that, in the circuit of Figure 9, first transistor 128 and second transistor 142 take the form of matched MOSFETs (“matched”, in this context, corresponds with the use of “matched” above). The skilled person will understand that the operation of the circuit of Figure 9 is similar to that of the circuit of Figure 2, subject to minor differences due to the substitution of MOSFETs for BJTs.

Figure 10 shows an alternative version of the circuit of Figure 4, in which components that correspond with components in Figure 4 are indicated with like reference signs. The difference between Figure 10 and Figure 4 is that first transistor 128 and second transistor 142 are PNP BJTs in the circuit of Figure 10. The different operating characteristics of PNP BJTs means that first resistor 136 and second resistor 150 are disposed on the ground side of first transistor 128 and second transistor 142 respectively. Figure 9 also shows MOSFET 114, which in contrast to MOSFET 114 in Figure 4, takes the form of a P-channel MOSFET. Again, the skilled person will understand that the operation of Figure 10 is similar to that of the circuit of Figure 2, subject to minor differences due to the use of NPN BJTs and a P-channel MOSFET.

The skilled person will appreciate that any other type of transistor may be used in place of first transistor 128 and second transistor 142.

In addition, the skilled person will appreciate that the current limiting circuits described herein can be viewed as modified current-mirrors, in which each “leg” of the current mirror experiences a different potential difference across it due to the impact of the potential drop across a shunt resistance. Accordingly, alternative versions of current mirror circuits may be employed, with suitable modification.

For example, one or more degeneration resistors may be employed, as will be understood by the skilled person. Alternatively, or in addition, the modified current mirror can be based on a Wilson current mirror circuit, a Widlar current mirror circuit, or a cascoded current mirror circuit, or other known modification of a basic current mirror circuit. The skilled person will appreciate that other modifications and improvements based upon known alternative current-mirror circuits can also be employed. Minor adjustments may be required to accommodate the use of a modified current mirror as part of a current-limiting circuit, but such adjustments are within the common general knowledge of the skilled person.

The skilled person will appreciate that references to control terminals may refer to a control terminal of a transistor (e.g., the base of a BJT, or the gate of a FET) or other semiconductor switch, or a similar control terminal of a circuit comprising several components. The skilled person will also appreciate that references to resistances may refer to one or more resistors in series and/or parallel, but can also include reactive, non-linear, or controllable components such as transistors, diodes, capacitors, and inductors, which are controllable or have an impedance that varies with frequency. The required adjustments to account for these different components are within the common general knowledge of the skilled person.

Although various specific implementations have been described, the skilled person will appreciate that the invention may be implemented in other manners.

CLAIMS

1. A circuit for limiting current through a conductor, the circuit comprising:
a current modulating circuit connected in series with the conductor, the current
modulating circuit comprising a current modulating circuit control terminal;
5 a shunt resistance connected in series with the current modulating circuit;
a current-to-voltage converter connected between a first input voltage and a first
side of the shunt resistance, the current-to-voltage converter comprising:
a first control terminal; and
a first primary current path through the current-to-voltage converter, the
10 first primary current path comprising a first series resistance;
a voltage-to-current converter connected between a second input voltage and a
second side of the shunt resistance opposite the first side of the shunt resistance, the
voltage-to-current converter comprising:
a second control terminal; and
15 a second primary current path through the current-to-voltage converter,
the second primary current path comprising a second series resistance;
wherein:
the first and second control terminals are coupled to each other, and to the first
primary current path;
20 the current modulating circuit control terminal is coupled to receive a control
signal from the first primary current path; and
wherein values of the first series resistance, second series resistance, and shunt
resistance are selected such that, as the current in the conductor increases, a corresponding
increase in voltage across the shunt resistance causes a reduction in current flow through
25 the first primary current path, which in turn causes a change in the control signal such
that current flow through the current modulating circuit is reduced.
2. The circuit of claim 1, wherein the first input voltage and the second input voltage
are the same .

3. The circuit of claim 1 or 2, wherein the values of the first series resistance, second series resistance, and shunt resistance are selected such that a voltage at the current modulating circuit control terminal approaches an operating threshold of the current modulating circuit for a voltage drop across the shunt resistance of less than 0.4 V.

5

4. The circuit of claim 3, wherein the values of the first series resistance, second series resistance, and shunt resistance are selected such that the voltage at the current modulating circuit control terminal approaches the operating threshold of the current modulating circuit for a voltage drop across the shunt resistance of less than 0.2 V.

10

5. The circuit of any preceding claim, wherein the first series resistance is at least ten times the second series resistance.

6. The circuit of any preceding claim, wherein the first series resistance is at least fifty times the second series resistance.

15

7. The circuit of any preceding claim, wherein the conductor forms part of a power supply circuit supplied by a battery.

8. The circuit of claim 7, wherein the circuit is configured to control current flow through the conductor such that the battery cannot supply more than 15 W to a further circuit for which the conductor forms part of a power supply circuit.

20

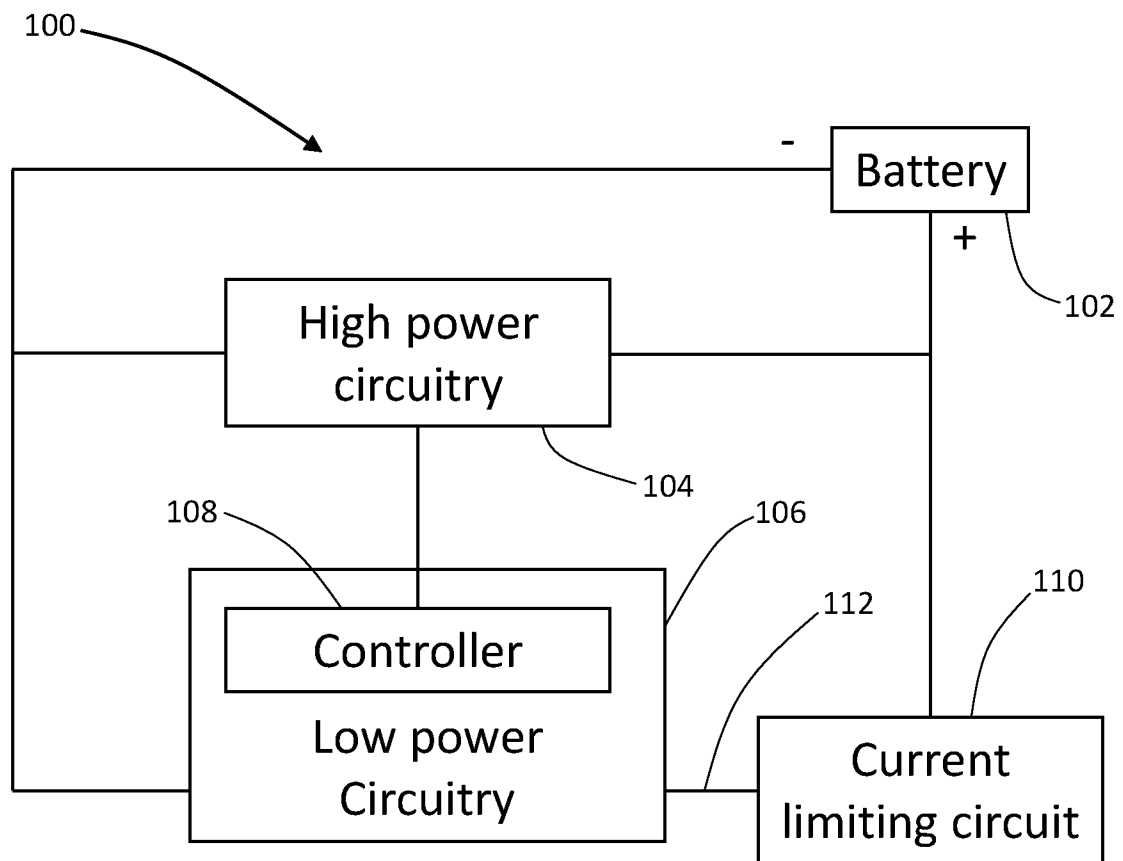
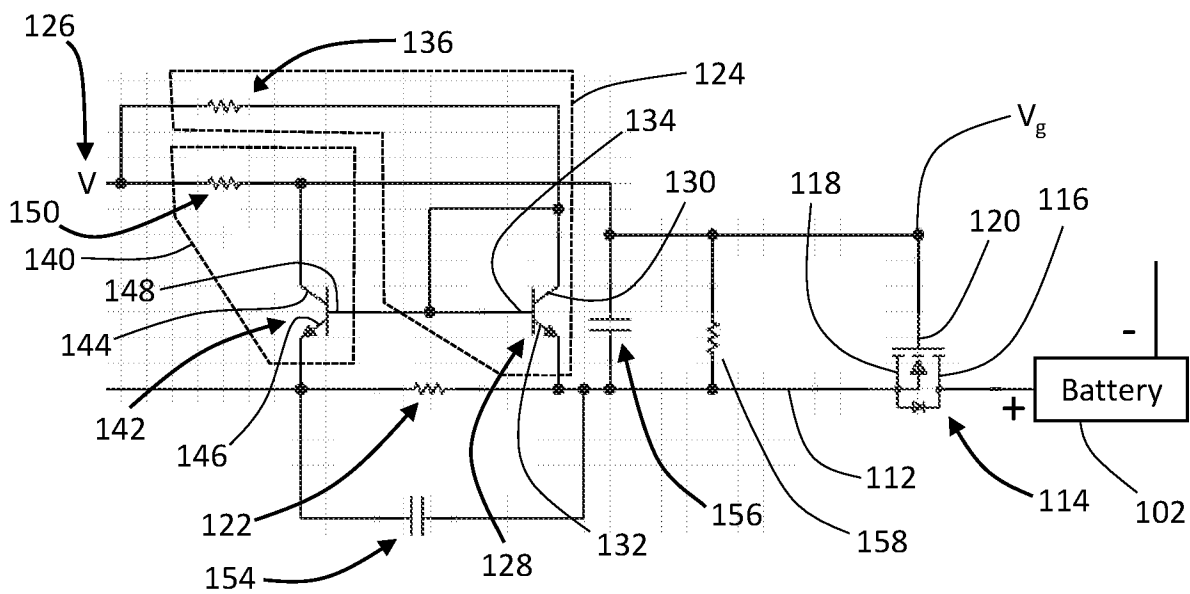
9. The circuit of any preceding claim, wherein the current-to-voltage converter and the voltage-to-current converter use at least one of the same type of transistor.

25

10. The circuit of claim 9, wherein the transistors are gain-matched to within at least 70% of each other.

11. The circuit of claim 9 or 10, wherein connection of the first and second control terminals to the first current path is made between the first series resistance and the transistor of the current-to-voltage converter.
- 5 12. An appliance comprising the circuit of any one of the preceding claims.
13. The appliance of claim 12, comprising a battery, a terminal of the battery being coupled to the conductor.
- 10 14. The appliance of claim 12 or 13, comprising high power circuit for driving a motor and/or heating element, and low power circuitry including control circuitry for controlling the high power circuit, the low power circuitry being powered via the conductor.

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Figure 1Figure 2

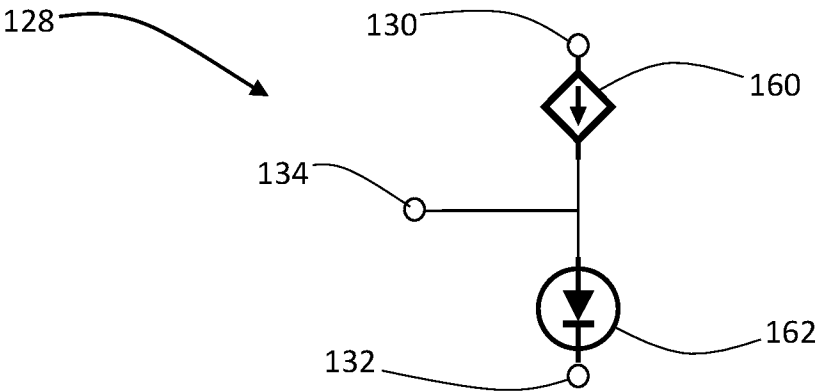


Figure 3

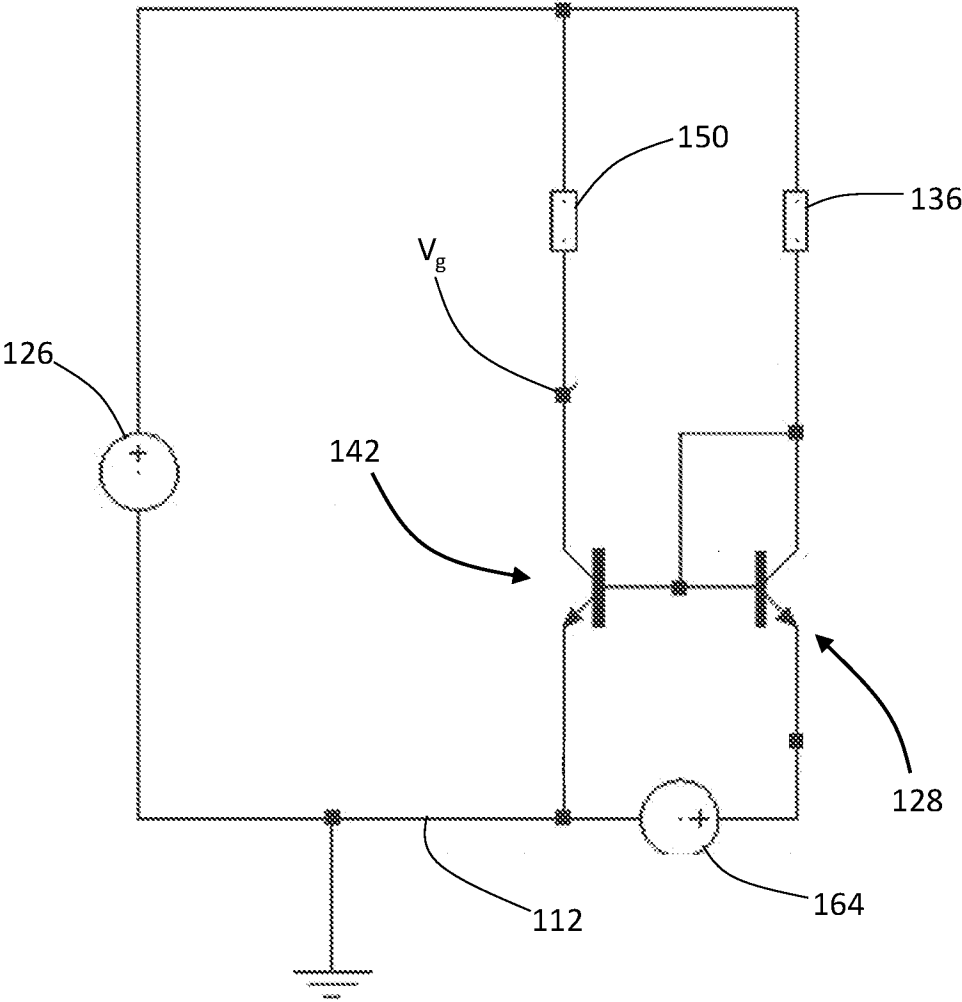


Figure 4

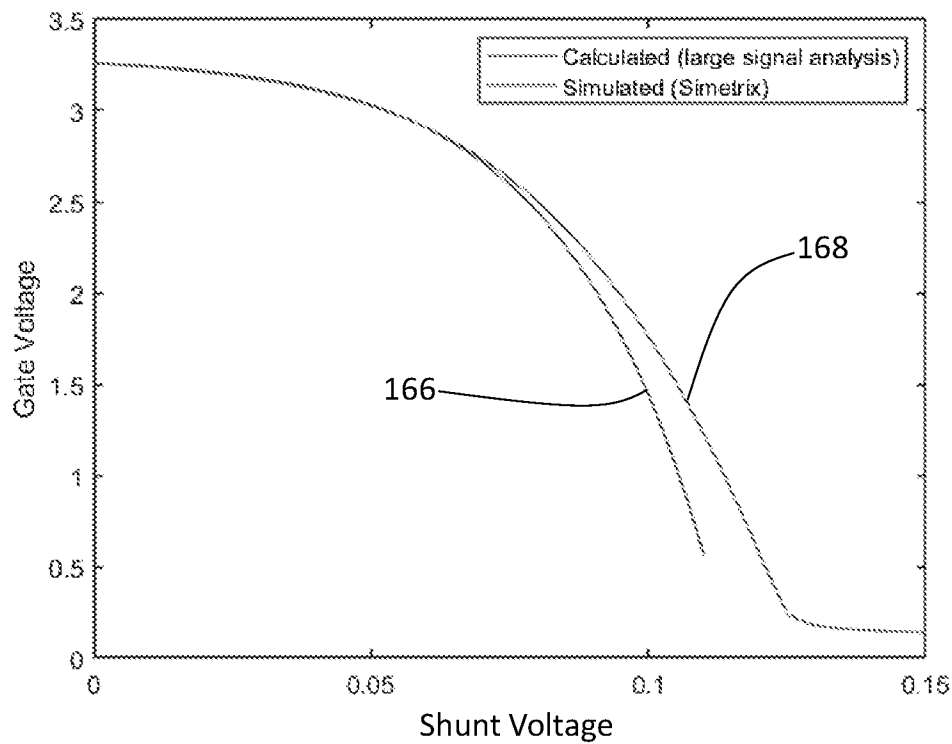


Figure 5

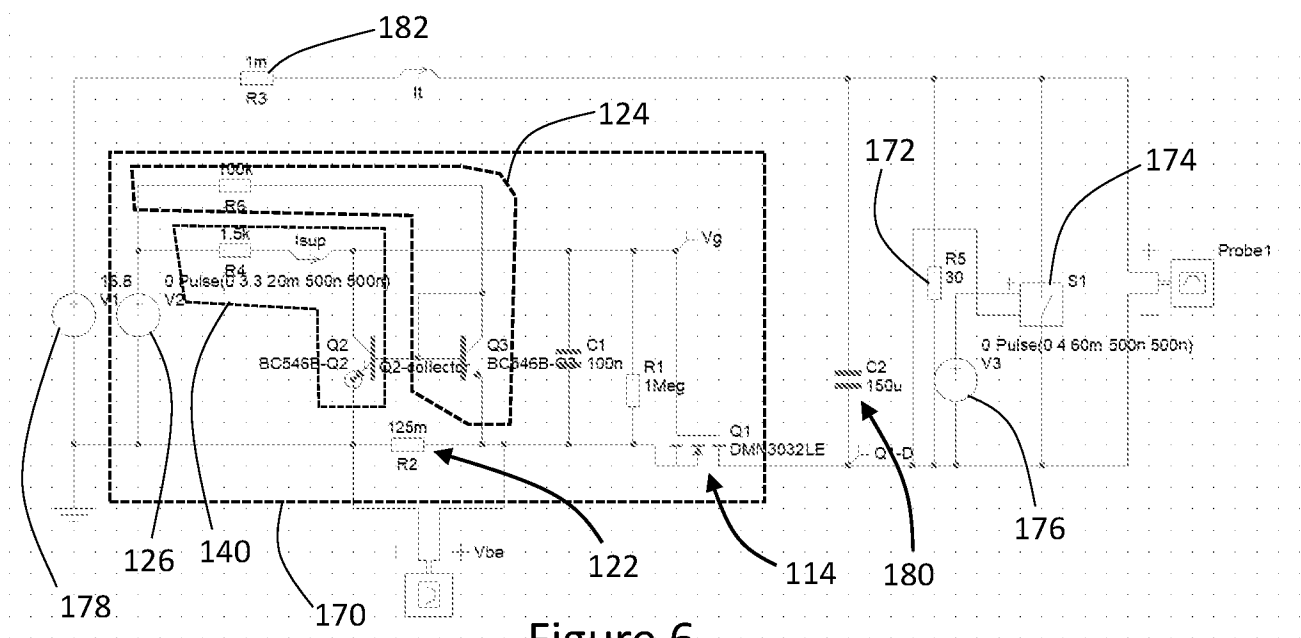


Figure 6

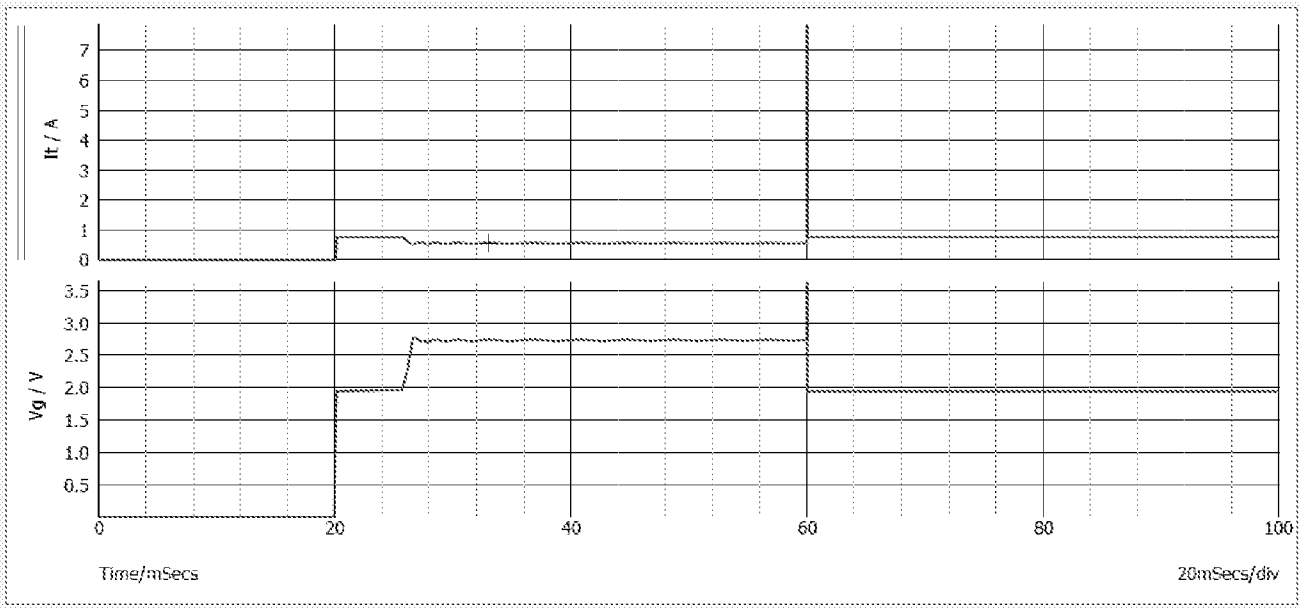


Figure 7

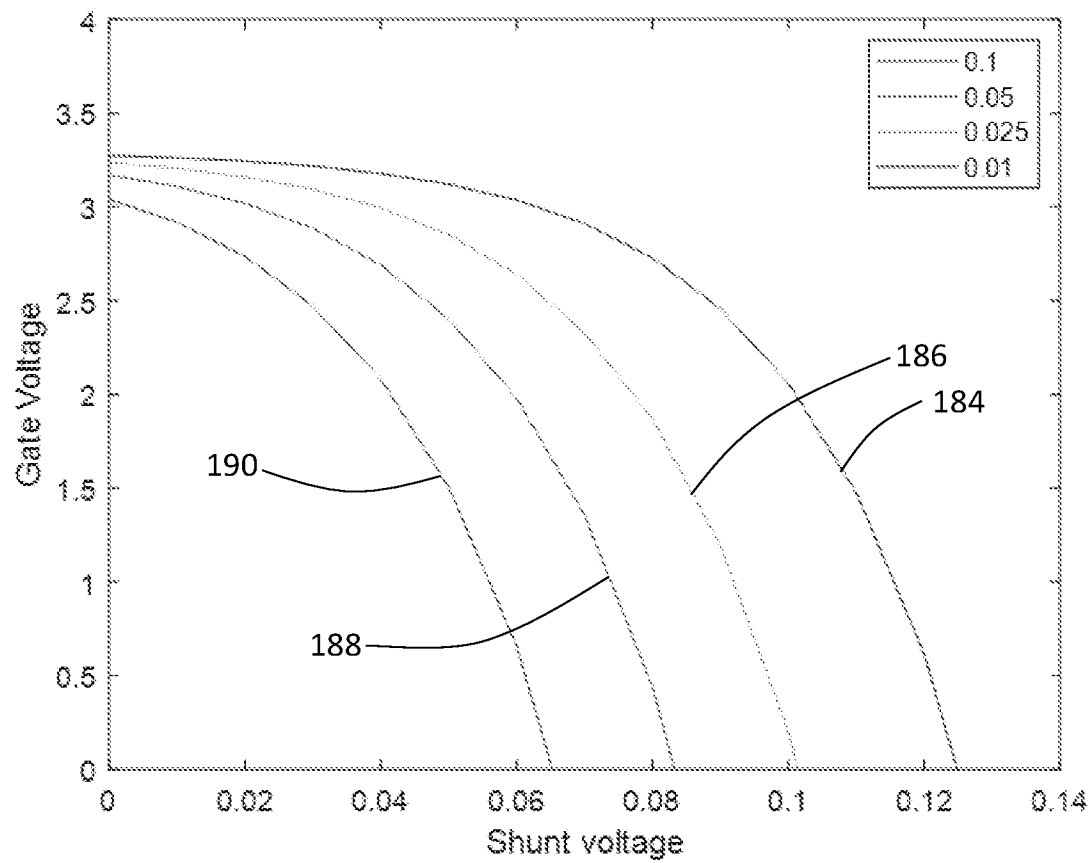


Figure 8

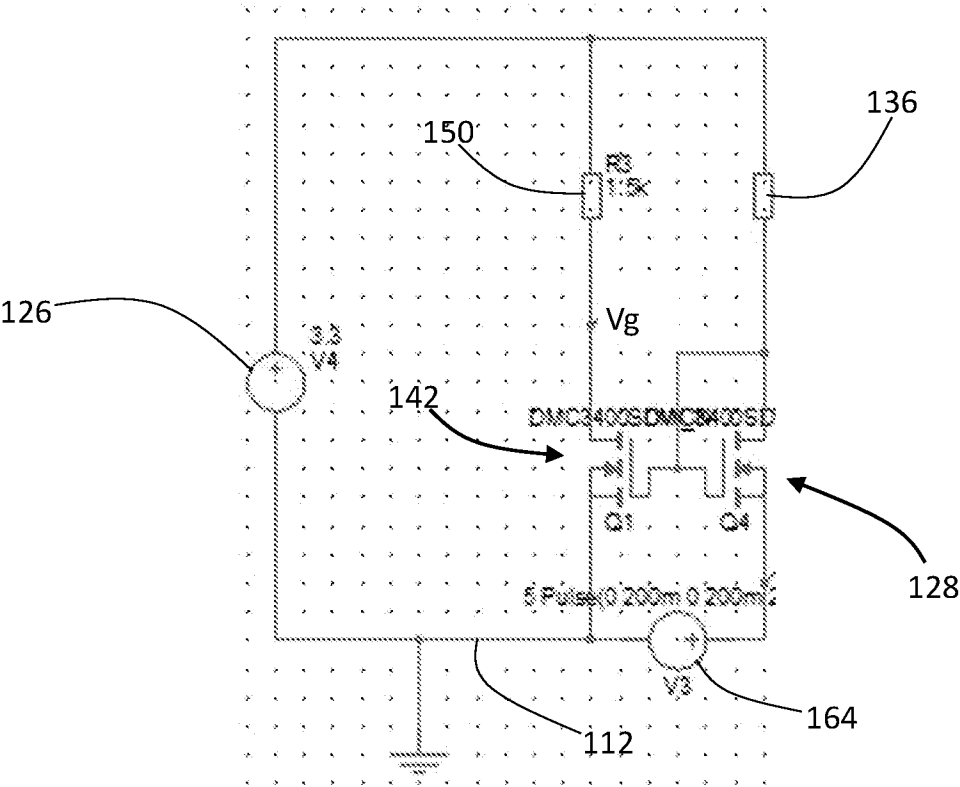


Figure 9

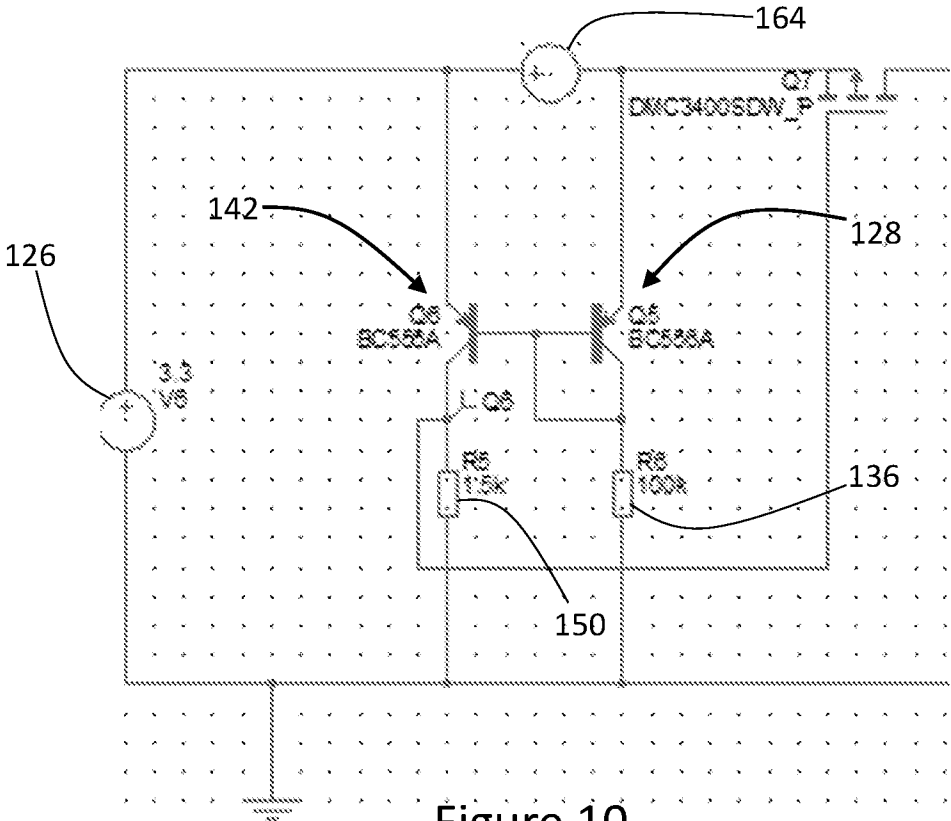


Figure 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2023/054683

A. CLASSIFICATION OF SUBJECT MATTER INV. G05F3/20 H02H9/02 H03K17/082 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) G05F H03K H02H		
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) EPO-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	US 2022/077763 A1 (DOMENGER LAURENT [FR] ET AL) 10 March 2022 (2022-03-10) abstract; figure 2 -----	1-14
A	DE 198 44 465 A1 (SIEMENS AG [DE]) 13 April 2000 (2000-04-13) abstract; figure 1 -----	1-14
A	US 5 939 921 A (STRAUSS SILVESTER [AT] ET AL) 17 August 1999 (1999-08-17) abstract; figure 2 -----	1-14
A	US R E37 778 E (FELDTKELLER MARTIN [DE]) 2 July 2002 (2002-07-02) figure 2 -----	1-14
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 21 July 2023		Date of mailing of the international search report 28/07/2023
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		Authorized officer Arias Pérez, Jagoba

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2023/054683

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 44 29 716 C1 (SIEMENS AG [DE]) 1 February 1996 (1996-02-01) abstract; figure 2 -----	1-14
A	DE 102 26 082 A1 (INFINEON TECHNOLOGIES AG [DE]) 8 January 2004 (2004-01-08) abstract; figure 1 -----	1-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2023/054683

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 2022077763	A1	10-03-2022	CN 113228513 A	06-08-2021
			EP 3900187 A1	27-10-2021
			FR 3091082 A1	26-06-2020
			JP 7232333 B2	02-03-2023
			JP 2022514095 A	09-02-2022
			KR 20210097806 A	09-08-2021
			US 2022077763 A1	10-03-2022
			WO 2020127196 A1	25-06-2020

DE 19844465	A1	13-04-2000	NONE	

US 5939921	A	17-08-1999	DE 19633367 A1	26-03-1998
			EP 0825716 A2	25-02-1998
			JP 3389471 B2	24-03-2003
			JP H10135804 A	22-05-1998
			US 5939921 A	17-08-1999

US RE37778	E	02-07-2002	DE 19707708 A1	03-09-1998
			EP 0965169 A1	22-12-1999
			JP 2001513281 A	28-08-2001
			KR 20000075637 A	26-12-2000
			US RE37778 E	02-07-2002
			WO 9838738 A1	03-09-1998

DE 4429716	C1	01-02-1996	NONE	

DE 10226082	A1	08-01-2004	NONE	
