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(54) Driver device for LEDs, and a method for providing electric current to LEDs

(57) A driver device (201) for light-emitting diodes (204) comprises a controllable first power source (202) that produces a first voltage (V_{in}) at its output. The magnitude of said first voltage depends on a control signal (206). A buck converter (203) has an input coupled to the output of said first power source, and an output for coupling light-emitting diodes thereto. A load voltage indicator (205) is configured to produce an indication signal depending a load voltage required by a load coupled to the output of said buck converter. A feedback coupling couples said indication signal as a control signal (206) to said controllable first power source.

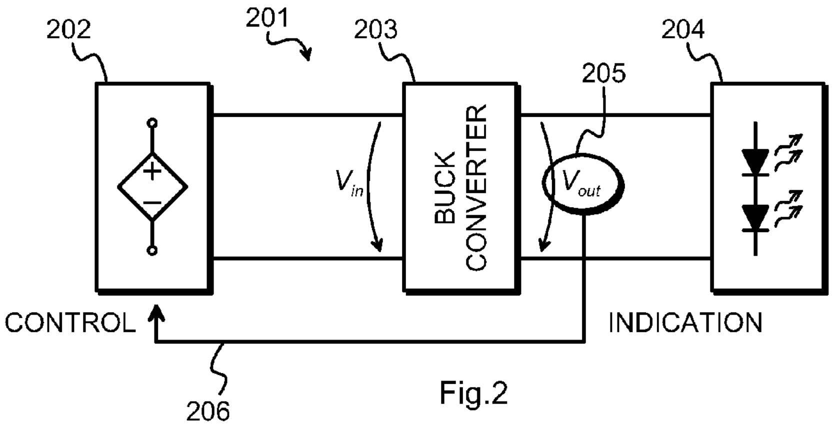

Fig.2

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Description

TECHNICAL FIELD

[0001] The invention concerns generally the field of controllably feeding electric current to a number of LEDs (light-emitting diodes) for lighting purposes. Especially the invention concerns a way of ensuring that high efficiency can be maintained, and the need for large and expensive inductive components can be avoided, even if a driver device leaves its user with considerable freedom concerning the number and mutual connections of LEDs to which the driver device will feed current.

BACKGROUND OF THE INVENTION

[0002] LEDs and LED chains must be fed with electric current of controlled magnitude in order to maintain the emission intensity and color at desired values. It has become customary to equip a LED lighting arrangement with a so-called driver device, the task of which is to ensure that the voltage across the load that includes the LEDs remains at an appropriate value. A buck converter is a popular choice as the basic building block of the driver device, because it combines relatively simple configuration with good efficiency and well-known operational principles.

[0003] Fig. 1 illustrates a known driver device 101, in which a buck converter is configured to feed electric current to a LED chain 102. A DC voltage V_{in} appears at the input terminals of the buck converter. From the first input terminal 103 there is a current path to the second input terminal 104, along which are a controllable switch 105, an inductor 106, the LED chain 102, and a current-sensing resistor 107. The point between the switch 105 and the inductor 106 is coupled to the cathode of a diode 108, the anode of which is coupled between the current-sensing resistor 107 and the second input terminal 104. A capacitor 109 is coupled in parallel with the load, i.e.with the LED chain 102. A control circuit 110 is configured to control the switch 105 on the basis of a current measurement, for the implementing of which the control circuit 110 is shown to have couplings to both ends of the current-sensing resistor 107. The current-sensing resistor could also be somewhere else along a current path that carries the load current or a current directly proportional to it.

[0004] When the switch 105 is closed, an increasing electric current flows to the inductor 106 and stores energy in its magnetic field. The diode 108 is reverse biased. When the switch 105 is opened, the energy discharging from the magnetic field of the inductor 106 causes current to flow in the loop that consists of the inductor 106, the LED chain 102, the current-sensing resistor 107, and the diode 108, of which the last-mentioned is now forward biased. The voltage V_{out} across the load is smoothened through the effect of the capacitor 109.

[0005] We may assume that in the example of fig. 1 the control circuit 110 applies so-called current hysteresis control. This means that when, during the conduction period of the switch 105, the current through the load (which is sensed as the voltage across the current-sensing resistor 107) reaches a predetermined maximum value, the control circuit 110 opens the switch 105. The current through the load starts to decrease, and would ultimately decrease to zero, if the whole energy stored in the inductor 106 and the capacitor109 would be allowed to discharge. When the current has reached a predetermined minimum value, the control circuit 110 closes the switch 105 again and the cycle starts anew. The difference between the predetermined current maximum and minimum values is called the current hysteresis or ripple.

[0006] It is relatively straightforward to optimise the component values in a connection device like that in fig. 1 for a constant number of LEDs in the LED chain 102. However, if the driver device should have more general applicability, for example so that it should work well with any number between 9 and 27 LEDs in the LED chain 102, the problem becomes more complicated. Each LED in a LED chain has a voltage drop, which can be for example 3.3 volts. A LED chain of 9 such LEDs thus requires an output voltage V_{out} = 29.7 volts, while a LED chain of 27 such LEDs requires an output voltage V_{out} = 89.1 volts. A large difference between the input and output voltages of the buck converter makes the conduction interval through the switch 105 short, so most of the time current flows through the diode 108 causing relatively high conduction losses. A large input/output voltage difference also increases the switching frequency of the buck converter, which leads to increasing switching losses in the switch 105 (which is typically a field-effect transistor).

SUMMARY OF THE INVENTION

[0007] According to an aspect of the invention, a driver device is provided for light-emitting diodes, which driver device accepts a wide range of LED arrangements as a load, and is still capable of efficient operation and low losses. According to another aspect of the invention, a driver device is provided that can be built from affordable components and still matches a wide range of output specifications. According to yet another aspect of the invention, there is provided a versatile method for providing electricity to light-emitting diodes with high efficiency and wide applicability.

[0008] In order to achieve these and further objectives it is advantageous to control the generation of the voltage that acts as the input voltage to the buck converter. Especially it is advantageous to compare a voltage difference between the input of the buck converter and the output of the buck converter to a target value and to use an indication of the comparison result as a control signal in the generation of the input voltage to the buck converter. By keeping the difference between the input and output voltages of the buck converter within a predetermined range, or even constant, it is possible to largely prevent or at least decrease the changes in duty cycle and switching frequency that would otherwise occur. Thus the component values of the buck converter are optimal or nearly optimal for a wide range of LED arrangements that can be coupled to it as a load.

[0009] The control principle according to embodiments of the invention can be easily coupled with a dimming arrangement, with which the desired lighting intensity of the LEDs can be varied. A control unit can repeatedly issue on and off commands to the buck converter with a pulse frequency that is preferably higher than 100 Hz but significantly lower than the switching frequency of the buck converter. During the on-periods the buck converter may apply current hysteresis control or some other control principle to provide electricity to the LEDs. The relative lengths of the on- and off-periods determine the lighting intensity that a human observer will perceive.

[0010] The exemplary embodiments of the invention presented in this patent application are not to be interpreted to pose limitations to the applicability of the appended claims. The verb "to comprise" is used in this patent application as an open limitation that does not exclude the existence of also unrecited features. The features recited in depending claims are mutually freely combinable unless otherwise explicitly stated.

[0011] The novel features which are considered as characteristic of the invention are set forth in particular in the appended claims. The invention itself, however, both as to its construction and its method of operation, together with additional objects and advantages thereof, will be best understood from the following description of specific embodiments when read in connection with the accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

[0012]

Fig. 1 illustrates a known driver device for LEDs,

fig. 2 illustrates schematically a driver device for LEDs according to an em-bodiment of the invention,

fig. 3 illustrates a buck converter that can be used in a driver device accord-ing to an embodiment of the invention,

fig. 4 illustrate current hysteresis control,

fig. 5 illustrates switching frequencies in an exemplary case if the invention is applied or is not applied,

fig. 6 illustrates schematically a driver device for LEDs according to an em-bodiment of the invention,

fig. 7 illustrates varying the input/output voltage difference of the buck con-verter as a function of output voltage,

fig. 8 illustrates a driver device according to an embodiment of the invention,

fig. 9 illustrates a driver device according to another embodiment of the in-vention,

fig. 10 illustrates a driver device according to another embodiment of the in-vention,

fig. 11 illustrates a driver device according to another embodiment of the in-vention,

fig. 12 illustrates some timing considerations when output voltage changes,

fig. 13 illustrates some timing considerations during PWM control, and

fig. 14 illustrates a method according to an embodiment of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0013] Fig. 2 illustrates schematically a driver device 201 for light-emitting diodes or LEDs. It comprises a controllable first power source 202, which is configured to produce a first voltage at its output. The magnitude of said first voltage depends on a control signal that in fig. 2 comes to the first power source 202 from below. The driver device 201 comprises a buck converter 203, which has an input coupled to the output of the first power source 202. The buck converter 203 has an output for coupling light-emitting diodes thereto. The LEDs are shown schematically as a block 204 in fig. 5. For the purposes of this description it is sufficient to assume that block 204 comprises for example a LED chain of N essentially equally dimensioned LEDs, so that in order to make the LEDs emit light, the voltage delivered to block 204 needs to equal N times the voltage drop across an individual LED.

[0014] The driver device 201 comprises a load voltage indicator 205, which is configured to produce an indication signal depending on a load voltage that is required by a load coupled to the output of the buck converter 203, and a feedback coupling 206 configured to couple said indication signal as a control signal to the controllable first power source 202.

[0015] To provide some background to understanding the significance of the entities 205 and 206 in fig. 2, we may consider the operation of the block illustrated as the buck converter 203 in fig. 2 in more detail. Fig. 3 is a simplified general representation of a buck converter, known parts of which carry the same reference designators as the corresponding parts in fig. 1. Fig. 4 illustrates schematically the current *i* fed to the LED chain 102. Considering the conduction period of the switch 105, and assuming that the current *i* changes essentially linearly, an equation can be written that links together the input and output voltages V_{in} and V_{out}, the change of current Δi, the inductance L of the inductor 106, as well as the duration t_{on} of the conduction period:

$$V_{in} - V_{out} = L \cdot \frac{\Delta i}{t_{on}} \tag{1}$$

[0016] Similarly for the non-conducting period of the switch 105 the following equation is true:

$$-V_{out} - V_{D1} = L \cdot \frac{-\Delta i}{t_{off}} \tag{2}$$

[0017] Here V_{D1} is the voltage drop across the diode 108. From equations (1) and (2) an expression can be derived for the output voltage V_{out} of the buck converter, which shows that apart from the constant parameter V_{D1}, the output voltage V_{out} depends only on the input voltage V_{in} and on the relative lengths of the conduction and non-conducting periods of the switch 105:

$$V_{out} = \frac{t_{on}}{t_{on} + t_{off}} \cdot V_{in} - \frac{t_{off}}{t_{on} + t_{off}} \cdot V_{D1} \tag{3}$$

[0018] Also another expression can be derived from equations (1) and (2), showing an interesting dependency of the switching frequency f_{sw} of the buck converter on the voltage difference V_{in} - V_{out}:

$$f_{sw} = \frac{1}{t_{on} + t_{off}} = \frac{1}{\Delta i \cdot L} \cdot \frac{(V_{in} - V_{out}) \cdot (V_{out} + V_{D1})}{V_{in} + V_{D1}} \tag{4}$$

[0019] As an example we may consider a buck converter, the input voltage V_{in} of which is 100 V, and assume that it can be coupled to feed current to a LED chain that can have any number of LEDs between 9 and 27, the ends included. The output voltage V_{out} required of the buck converter is thus between 29.7 volts and 89.1 volts. For the purpose of this example we further assume that Δi = 70 mA, L = 1 mH, and V_{D1} = 0.7 V. Curve 501 in fig. 5 illustrates how the switching frequency of the buck converter varies, having a maximum value over 350 kHz at the output voltage 50 V and dropping below 150 kHz when the output voltage approaches 90 V.

[0020] According to an aspect of the invention, let us assume that the input voltage V_{in} of the buck converter is not kept constant, but at a value that is a certain voltage difference V_{ctrl} above the output voltage V_{out}:

$$V_{in} = V_{out} + V_{ctrl} \tag{5}$$

[0021] Making in equation (1) the substitution expressed in equation (5) yields

$$V_{ctrl} = L \cdot \frac{\Delta i}{t_{on}} \tag{6}$$

from which we may derive an expression for the duration t_{on} of the conduction period:

$$t_{on} = \frac{L \cdot \Delta i}{V_{ctrl}} \tag{7}$$

[0022] A corresponding expression can be derived from equation (2) for the duration t_{off} of the non-conducting period:

$$t_{off} = \frac{L \cdot \Delta i}{V_{out} + V_{D1}} \tag{8}$$

using in equation (4) the substitutions expressed in equations (7) and (8) gives now the switching frequency f_{sw} of the switch the following form:

$$f_{sw} = \frac{1}{t_{on} + t_{off}} = \frac{1}{\Delta i \cdot L} \cdot \frac{V_{ctrl} \cdot (V_{out} + V_{D1})}{V_{ctrl} + V_{out} + V_{D1}} \tag{9}$$

[0023] Plotting the switching frequency f_{sw} given by equation (10) shows that it varies much less as a function of the output voltage V_{out} than the one given by equation (4) above. Curve 502 in fig. 5 shows the switching frequency of an exemplary buck converter, when the voltage difference V_{ctrl} is constant at 10 volts. The inductance L of the inductor illustrated as 106 in fig. 3 is now 500 μH, i.e. only half of the value used to calculate curve 501, but otherwise the calculation parameters are the same. It is easy to see that the variation of the switching frequency over the whole output voltage range is now only some 15% of the maximum frequency, while in the case illustrated by curve 501 it was well over 60%.

[0024] We may now return to the schematically illustrated driver device 201 of fig. 2. The purpose of the load voltage indicator 205 is to produce an indication signal depending on a load voltage required by block 204. If this indication signal or some unambiguous derivative thereof is used to control the controllable first power source 202, it is possible to vary the voltage V_{in} in synchronism with variations in the voltage V_{out}, so that there is always a predetermined voltage difference between them.

[0025] The invention leaves certain freedom in the implementation of a load voltage indicator. Fig. 6 illustrates one advantageous approach. In order to reduce the variation in switching frequency, the driver device 601 comprises a comparator 605 that is configured to compare a voltage difference between the input and the output of the buck converter 203 to a target value, and to produce the indication signal as an indication of how much said voltage difference differs from the target value. Additionally the driver device comprises a feedback coupling 606 configured to couple said indication signal as a control signal to the controllable first power source 202.

[0026] Remembering that the controllable first power source 202 is configured to produce the voltage V_{in} so that its magnitude is dependent on the control signal, the effect of using the comparator 205 and the feedback coupling 206 is that the input voltage V_{in} to the buck converter 203 is made to follow the voltage V_{out} (which is essentially determined by the number of serially coupled LEDs in block 204) at a predetermined offset. According to one embodiment of the invention, the configured effect of the feedback coupling 206 is to control the output voltage of the controllable first power source 202 so that the voltage difference between the input and output of the buck converter 203 remains within predetermined limits of a constant, and preferably equal to said constant. As we have shown above with reference to equation (9) and curve 602 in fig. 6, this has the effect that the switching frequency of the buck converter 203 changes only relatively little even if the voltage V_{out} required by block 204 varies within a relatively wide range.

[0027] It is even possible to keep the switching frequency f_{sw} constant over the whole range of the output voltage V_{out}, by varying the voltage difference V_{ctrl}. Solving equation (9) for V_{ctrl} gives

$$V_{ctrl} = \frac{f_{sw} \cdot \Delta i \cdot L \cdot \left(V_{out} + V_{D1}\right)}{V_{out} + V_{D1} - \left(f_{sw} \cdot \Delta i \cdot L\right)} \qquad (10)$$

which constitutes an unambiguous definition of the voltage difference V_{ctrl} as a function of the output voltage V_{out}, if all other factors (including the switching frequency f_{sw}) on the right side of the equation are constants. Curve 701 in fig. 7 illustrates the voltage difference V_{ctrl} as a function of the output voltage V_{out}, when the values f_{sw} = 250 kHz, Δi = 70 mA, L = 0.5 mH, and V_{D1} = 0.7 V are used.

[0028] Fig. 8 illustrates in a slightly more detailed manner a driver device for LEDs according to an embodiment of the invention. Here we assume that the first power source mentioned above, the task of which is to produce the input voltage for the buck converter, is a switched-mode power supply. It comprises an inductive element, which here is the primary coil of a transformer 801, and a primary current switch 802 coupled in series with said inductive element. Repeatedly switching on and off the current through the inductive element according to a duty cycle causes energy to be repeatedly stored into and discharged from its magnetic field. In the embodiment shown in fig. 8 discharging energy takes place through a secondary winding of the transformer 801, and the discharged energy is converted into a voltage with the help of a diode 803 and a capacitor 804. The duty cycle of the switched-mode power supply is configured to be proportional to the value of an indication signal indicative of how much the voltage difference of a subsequent buck converter differs from the target value, in a manner described in more detail below.

[0029] The input voltage of the buck converter appears across the capacitor 804, which constitutes the output of the switched-mode power supply. The buck converter comprises a controllable switch 105 that has a conducting state, in which it is configured to conduct electric current from the output of the switched-mode power supply (here: from the positive electrode of the capacitor 804), and a non-conducting state. The buck converter comprises also an LC circuit that comprises an inductor 106, a capacitor 109, and a flywheel switch (here: diode) 108. The LC circuit is configured to receive electric current through the controllable switch into the inductor 106 during the conducting state of the controllable switch. The LC circuit is also configured to deliver current from the inductor 106 into a loop comprising the inductor 106, the flywheel switch 108, and a load (here: LED chain 102) coupled to the output of the buck converter, during a non-conducting state of the controllable switch 105.

[0030] The buck converter comprises further a control circuit 805, which is configured to repeatedly change the state of the controllable switch 105 based on a measured momentary current through the buck converter. Measuring the momentary current through the buck converter takes place in a current sensing resistor 107, which is here located so that the current goes through it both during the conducting state and during the non-conducting state of the controllable switch 105. More exactly, there is a current path from the positive output node of the first voltage source to the negative one, along which are the controllable switch 105, the inductor 106, the LED chain 102, and the current sensing resistor 107. The diode that acts as a flywheel switch 108 has its anode coupled to the negative output node of the first power source and its cathode coupled between the controllable switch 105 and the inductor 106. A capacitor 109 is coupled in parallel with the LED chain 102. As such, the configuration and operation of the buck converter does not differ from what has been explained in the description of prior art in association with fig. 1. A different reference designator 805 is used for the control circuit in order to emphasize its ability to respond to so-called PWM commands, which will be described in more detail later.

[0031] The comparator and feedback coupling are illustrated in the lower part of fig. 8. In order to take a sample of the voltage at the output of the buck converter, there is a diode 806, the anode of which is coupled to the positive node of the buck converter output, i.e. the point between the inductor 106 and the LED chain 102. The cathode of the diode 806 is coupled to a capacitor 807, the other electrode of which is coupled to the ground potential of the buck converter. From the point between the diode 806 and the capacitor 807 there is a connection through a voltage divider 808 to the non-inverting input of a differential amplifier 809. To the inverting input of the differential amplifier 809, a sample of the voltage at the input of the buck converter is taken through a zener diode 810 and another voltage divider consisting of resistors 811 and 812. The cathode of the zener diode 810 is coupled to the positive output node of the switched-mode power supply, i.e. to the anode of the diode 803. The output of the differential amplifier 809 is configured to drive the LED of an optoisolator 813, the phototransistor side of which is coupled to a voltage controller 814 of the switched-mode power supply. The voltage controller 814 is responsible for forming and delivering the switching pulses to the primary current switch 802 of the switched-mode power supply.

[0032] As is evident from the description above, the switched-mode power supply that acts as the controllable first power source in fig. 8 comprises a transformer 801 that divides the switched-mode power supply to a primary side (leftmost part in fig. 8) and a secondary side (from the secondary coil of transformer 801 up to capacitor 804), with galvanic isolation between the primary and secondary sides. In order to maintain the galvanic isolation also in the feedback connection, the driver device of fig. 8 comprises a galvanically isolating signal transmitter (the optoisolator 813) for conveying the indication signal to the primary side of the switched-mode power supply. Galvanic isolation may be advantageous or even mandatory in electric devices that leave it free for the user to select and connect the load, because it increases security against accidental or intentional failures in selecting and connecting the load.

[0033] During operation, the zener diode 810 sets the voltage difference, for which the symbol V_{ctrl} has been used in the equations earlier, between the input and output of the buck converter. The voltage dividers at the inputs of the differential amplifier 809 are selected so that as long as the voltage difference between the input and output of the buck converter is larger than or equal to V_{ctrl}, the output of the differential amplifier 809 remains negative or zero. When the sample taken from the voltage at the output of the buck converter becomes larger than the one taken from the input, the output of the differential amplifier 809 becomes positive, and lits up the diode in the optoisolator 813. It is thus justifiable to say that the differential amplifier 809 acts as the comparator that compares a voltage difference between the input and output of the buck converter to a target value; here the target value is the reverse breakdown voltage of the zener diode 810. We may also say that the differential amplifier 809 is configured to produce an indication signal indicative of how much said voltage difference differs from said target value, even if in this case this is literally true concerning only differences in the direction where the difference is smaller than said target value.

[0034] Producing an indication signal depending on a load voltage required by a load coupled to the output of the buck converter does not require comparing the output voltage to the input voltage of the buck converter. Neither does it require a galvanic connection to the buck converter output. Fig. 9 illustrates a driver device according to an alternative embodiment of the invention, where the diode 806, the capacitor 807, and the voltage divider 808 are basically the same as in fig. 8. However, the anode of the diode 806 is now coupled to an auxiliary inductor 901 that is inductively coupled with the inductor 106 of the buck converter. As a difference to fig. 8, the coupling from the voltage divider 808 is now to the inverting input of the differential amplifier 809. The non-inverting input of the differential amplifier 809 is coupled to the cathode of a zener diode 902, the anode of which is coupled to the ground potential of the buck converter. From the non-inverting input of the differential amplifier 809 there is also a coupling through a resistor 903 to a feed voltage V_{cc}. The output of the differential amplifier 809 is coupled to the cathode of the LED in the optoisolator 813. The anode of said LED is coupled to the feed voltage V_{cc} through a resistor 904.

[0035] During the conduction period of the controllable switch 105 the voltage across the inductor 106 is equal to the difference between the input and output voltages of the buck converter. Due to the close inductive coupling and the chosen polarities, the voltage across the auxiliary inductor 901 follows the voltage across the inductor 106, scaled with the relation of the numbers of turns in the inductors. This voltage charges the capacitor 807, the capacitance of which is large enough so that it retains the voltage also during the non-conducting periods of the controllable switch 105 (when the dotted end of the auxiliary inductor 901 goes negative). The voltage V_{807} across the capacitor 807 can be calculated as

$$V_{807} = \frac{N_{901}}{N_{106}} \cdot \left(V_{in} - V_{out}\right) - V_{806} \qquad (11)$$

where N_{901} and N_{106} are the numbers of turns in the auxiliary inductor 901 and the inductor 106 respectively, V_{in} is the input voltage of the buck converter (i.e. the voltage across the capacitor 804), V_{out} is the output voltage of the buck converter (i.e. the voltage across the LED chain 102), and V_{806} is the forward voltage drop across the diode 806.

[0036] From equation (11) we see that the positive potential of the node between the diode 806 and the capacitor 807 in fig. 9 is directly proportional to the voltage difference between the input and output voltages of the buck converter. The differential amplifier 809 compares a sample of this positive potential to a fixed reference voltage generated with the zener diode 902, fed from the feed voltage V_{cc} through resistor 903. The larger the voltage difference across the buck converter, the more negative will go the output of the differential amplifier 809, and the brighter the LED will shine in the optoisolator 813. The voltage controller 814 of the switched-mode power supply must be built so that the stronger signal it receives through the optoisolator 813, the more it decreases the output voltage of the switched-mode power supply.

[0037] The embodiments of figs. 8 and 9 illustrate the well-known fact that in electronics, a number of possible ways, circuit architectures, and component configurations can be presented to implement a desired functionality, even if no programmable components are used. It should be noted that various parts of the circuit solution, e.g. the sampling of the input and output voltages, the comparison, and the conveying of a feedback signal, can be independently implemented in various ways, without being limited to the combinations shown here. For example the inductive way of sampling the output voltage illustrated in fig. 9 could easily be combined with the other features as shown in fig. 8, or inductive sampling could be used to replace the direct sampling of the input voltage of the buck converter illustrated in fig. 8. If the sampling of the voltages is done inductively (or otherwise without galvanic connection), the galvanically isolating signal transmitter on the feedback path may become unnecessary. In such a case the whole sampler and comparator circuitry would be galvanically connected to the primary side of the switched-mode power supply instead of its secondary side.

[0038] Fig. 10 illustrates an embodiment that offers even more versatility in the form of a functional block 1001 that may include or consist of programmable parts (although this is not a necessary requirement of the invention). The components and circuit architecture of the switched-mode power supply and the buck converter are here shown as equal to those in figs. 8 and 9, for reasons of simplicity. Sampling the input and output voltages of the buck converter is shown to be done with first and second voltage dividers 1002 and 1003 respectively. The comparator that is configured to compare the voltage difference between the input and output of the buck converter to a target value and to produce an indication signal indicative of how much said voltage difference differs from said target value, is included within the functional block 1001.

[0039] As an example, the functional block 1001 may comprise a microcontroller configured to execute a stored program. Such a solution is particularly versatile, for example because the stored program may be made to include all kinds of filtering functions and signal processing, for which additional analog circuit elements would otherwise be needed. With a program-executing microcontroller it is easy to implement e.g. the constant switching frequency embodiment of the invention, in which the target value of the voltage difference varies as a function of the magnitude of the output voltage of the buck converter (see fig. 7).

[0040] Fig. 11 illustrates another example of how applications of the invention are independent of particular circuit topology. In the embodiment of fig. 11 the parts of the switched-mode power supply as well as the (possibly microcontroller-based) comparator and feedback functions are similar to those in fig. 10, but the buck converter has a slightly different topology. In accordance with the known operating principle of a buck converter, it still comprises a controllable switch 105 as well as an LC circuit comprising an inductor 106, a capacitor 109, and a flywheel switch 108. The LC circuit is configured to receive electric current through the controllable switch 105 into the inductor 106 during a conducting state of the controllable switch 105, and to deliver current from the inductor 106 into a loop comprising the inductor 106, the flywheel switch 108, and a load (the LED chain 102) coupled to an output of the buck converter, during a non-conducting state of said controllable switch. Additionally the buck converter comprises a control circuit 1102 that is configured to repeatedly change the state of the controllable switch 105 based on a measured momentary current through the buck converter.

[0041] As a difference to the previously explained buck converters, the current path between the positive and negative output nodes of the switched-mode power supply now comprises the current-sensing resistor 107, the LED chain 102, the inductor 106, and the controllable switch 105 in this order. The cathode of the diode that acts as a flywheel switch 108 is coupled to the positive output node of the switched-mode power supply, and the anode of said diode is coupled between the inductor 106 and the controllable switch 105. The voltage at the output of the buck converter is sampled from between the inductor 106 and the LED chain 102 through the voltage divider 1101. The control circuit 1102, which is configured to repeatedly change the state of the controllable switch 105 between conducting and non-conducting states based on a measured momentary current through the buck converter, is illustrated with a different reference designator than before, because the different circuit topology may require some (very straightforward) changes in e.g. its internal component values. Different circuit topologies of buck converters, and the corresponding requirements for control circuitry, are as such known to the person skilled in the art.

[0042] In order to enhance stability, it is advantageous to make a time constant of controlling the switched-mode power supply (or other circuit arrangement used as the controllable first power source) significantly longer than one switching period of the controllable switch in the buck converter. In other words, changes in the input voltage of the buck converter should be relatively slow compared to changes in its output voltage. Several approaches can be taken to affect the time constant. Already the (typically relatively large) capacitance of the output capacitor of the controllable first power source is a factor. In analog solutions such as those illustrated in figs. 8 and 9, the transfer function of the differential amplifier circuitry can be tuned by selecting the auxiliary components properly. The voltage controller 814 of the controllable first power source may include filtering and integrating functions, and especially if a programmable entity is used as the functional block 1001 seen in figs. 10 and 11, the timing of the control loop can be quite freely selected.

[0043] Fig. 12 illustrates some timing considerations. We assume that a driver device according to an embodiment of the invention operates under steady state conditions, until at the time T illustrated with a vertical line across the graphs, the number of serially coupled LEDs in its load is suddenly decreased for example by closing a lossless switch that short circuits a number of LEDs in the LED chain. Before time T, the load current had varied between its minimum and maximum values according to the principle of current hysteresis control, drawing a regular sawtooth pattern. Corresponding to each increasing segment of the current graph there was a switching pulse of the controllable switch in the buck converter, and corresponding to each decreasing segment of the current graph the controllable switch in the buck converter was in its non-conducting state. The input voltage to the buck converter, which is illustrated in fig. 12 as the SMPS (switched-mode power supply) voltage, was steady and larger in magnitude than the output voltage of the buck converter.

[0044] Suddenly decreasing the number of LEDs at time T triggers a transition period. The immediate effect is a much steeper increase in the load current during the following switching pulse, which - according to the principle of current hysteresis control - causes that switching pulse to become relatively short. However, the discharging period is longer than before, which can be verified by solving equation (2) for t_{off} and noting that t_{off} is inversely proportional to the sum of V_{out} and V_{D1}. When the control of the voltage obtained from the switched-mode power supply starts to take effect, the difference between the input and output voltages of the buck converter becomes gradually smaller, until at time T' the transition period is over and the switching frequency of the buck converter has stabilized at or close to its previous value. In fig. 12 we assume that controlling the switched-mode power supply aims at keeping the voltage difference between V_{in} and V_{out} constant, instead of e.g. keeping the switching frequency f_{sw} constant. The time scale of fig. 12 has been made artificial for reasons of graphical clarity; typically it could take thousands or even millions of switching pulses in the buck converter for the change to take effect and for the transition period to reach its end at time T'.

[0045] It should be noted that sudden changes in the number of serially coupled LEDs in the load are seldom to be expected in practical situations. The ability of the driver device to adapt to different numbers of serially coupled LEDs in the load is typically more useful in the sense that the same or a similarly built driver device can be used in a variety of applications, that differ from each other in the number of serially coupled LEDs that need to be driven.

[0046] A driver device according to an embodiment of the invention is particularly well suited for applications where a controllable lighting intensity of the LEDs, commonly referred to as dimming, is desired. It is known that a dimming effect can be achieved by chopping the current delivered to the LEDs and varying the duty cycle of the chopping according to the PWM (pulse width modulation) principle. The PWM frequency should be high enough so that the human eye does not perceive any flickering of the LEDs. PWM frequencies over 100 Hz are usually considered sufficiently high.

[0047] Fig. 13 illustrates a principle of dimming applied in a driver device according to an embodiment of the invention. We assume that the buck converter comprises a control input for receiving on and off commands. In the embodiments of figs. 7 and 8 this control input was schematically shown as an input labeled PWM to the control circuit 805; in the embodiments of figs. 9 and 10 a corresponding input of the control circuit is shown as being coupled to the functional block 1001. We also assume that in order to implement dimming according to the PWM principle, the driver device comprises a control unit with an output coupled to said control input of the buck converter. In the embodiments of figs. 9 and 10 the control unit can be easily implemented as a part of the functional block 1001. Whatever its practical implementation, the control unit is configured to repeatedly issue on and off commands to the buck converter through its control input, in response to external commands indicative of a desired lighting intensity. The external commands may come, for example, from a lighting control knob or button operated by a human user, or from an automaton that aims at adjusting the lighting intensity to match the brightness of light in the environment.

[0048] In fig. 13 the rising edge of each PWM pulse means an on command and the trailing edge an off command. The second line of fig. 13 is a reminder that the on and off commands related to PWM control mean activating and deactivating the whole switching process in the buck converter. During each PWM pulse, the controllable switch of the buck converter repeatedly changes between conducting and non-conducting states at the switching frequency of the buck converter, whereas between PWM pulses the controllable switch of the buck converter remains nonconductive. Again, the relative time scales that are illustrated have been selected for graphical clarity; in practice the buck converter may execute hundreds or thousands of switching pulses during each PWM pulse. A pulse frequency of the on and off commands should be higher than 100 Hz in order to avoid perceivable flickering, and significantly lower than the switching frequency of the buck converter in order to ensure stabile operation.

[0049] PWM of current is an advantageous method for controlling the lighting intensity of LEDs, because the color of light emitted by the LEDs typically depends on the current. The PWM method means feeding pulses of essentially constant current through the LEDs and not feeding any current to them between the pulses. This is illustrated schematically on the third line of fig. 13, where the load current is seen to be zero between PWM pulses and oscillate (due to current hysteresis control) around an effective constant current value during each PWM pulse. The relatively coarse zig-zag pattern seen in the drawing is a consequence of heavily exaggerating the relative width of the switching pulses of the buck converter in relation to the width of the PWM pulses (and heavily exaggerating the current hysterersis, i.e. the margin Δi in which the load current is allowed to vary). In practice the load current graph will resemble a neat square wave.

[0050] The lowest line in fig. 13 emphasizes the fact that PWM control or other form of dimming should not interfere with controlling the input voltage that the switched-mode power supply or other kind of controllable first voltage source produces for the buck converter. This voltage is called here the SMPS voltage for short. Between PWM pulses the voltage delivered to the load (i.e. the output voltage of the buck converter) is zero. If one would stricly apply the principle of controlling the SMPS voltage on the basis of the difference between the input and output voltages of the buck converter, this would cause the SMPS voltage to drop between each SMPS pulse, and to raise back to its intended level during each SMPS pulse. By selecting the time constant of the SMPS voltage control long enough, such unnecessary wobbling in the SMPS voltage can be avoided or reduced to an acceptable level, which is illustrated in fig. 13 as the slight meandering of the SMPS voltage graph. It is also possible to implement the control in such a way that the beginning of a PWM pulse enables the control and the end of the PWM disables it, so that controlling the SMPS voltage on the basis of the difference between the input and output voltages of the buck converter is only applied during each PWM pulse.

[0051] As is illustrated in figs. 9 and 10, it is possible to implement the control unit that executes PWM control (i.e. repeatedly gives the on and off commands to the buck converter) within a common integrated circuit with the comparator that implements the comparing of voltages between the input and output of the buck converter. In an even further integrated solution the common integrated circuit additionally includes the control circuit of the buck converter, which control circuit is configured to repeatedly change the state of the controllable switch in the buck converter between conducting and non-conducting states based on a measured momentary current through the buck converter.

[0052] Fig. 14 illustrates schematically a method for providing electricity to light-emitting diodes according to an embodiment of the invention. It comprises producing a first voltage as illustrated in step 1401, and using a buck converter to convert said first voltage into an output voltage that is coupled across a chain of said light-emitting diodes, as illustrates in step 1402. In accordance with an embodiment of the invention, an indication signal should be produced depending on a load voltage required by a load coupled to an output of said buck converter. For this purpose, step 1403 illustrates comparing a voltage difference between the input of the buck converter and the output of the buck converter to a target value that may be constant or may vary e.g. as a function of the output voltage, as was explained earlier in association with equation (10). Step 1404 illustrates producing an indication signal indicative of how much said voltage difference differs from the target value, and step 1405 illustrates using said indication signal to control the magnitude of the first voltage.

[0053] If the target value applied in step 1403 is constant, step 1405 involves controlling the magnitude of said first voltage so that the voltage difference between the input and output voltages of the buck converter remains within predetermined limits of a constant, and preferably equal to said constant. Using the expression ""within predetermined limits" emphasizes the fact that no practically applied control is completely accurate, but aims at achieving a magnitude of the controlled quantity that is reasonably close to the target value. How close is reasonably close depends on the application environment, for example on the accuracy standards that the circuit arrangement should achieve.

[0054] If the circuit arrangement used to produce the first voltage in step 1401 is a switched-mode power supply, an advantageous and easily implemented way of using the indication signal to control the magnitude of the first voltage is to make a duty cycle of the switched-mode power supply proportional to a value of said indication signal. If dimming or other kind of controlling of a lighting intensity of the LEDs is desired, the method may comprise repeatedly switching the buck converter on and off at a frequency that is higher than what is needed to avoid perceivable flickering (e.g. higher than 100 Hz) but lower than a switching frequency of the buck converter. Forming the on and off commands to the buck converter at the PWM frequency for this purpose is illustrated in fig. 14 as step 1406.

[0055] A number of changes and modifications can be made to the embodiments explained above without departing from the scope of protection defined in the claims. For example, even if a diode has been consistently illustrated as the flywheel switch of a buck converter, it is possible and in some cases very much desirable to use some other form of a switch for this purpose. For example by replacing the diode with a field-effect transistor it is possible to lower the voltage drop V_{D1} over the flywheel switch and to decrease conduction losses during the non-conducting period of the actual controllable switch of the buck converter. If the flywheel switch too is a controllable switch, such as a field-effect transistor, it needs switching pulses of its own. However, as the conducting and non-conducting periods of the flywheel switch are an exact complement of the non-conducting and conducting periods of the actual controllable switch in the buck converter, the additional switching pulses for the controllable flywheel switch are easily produced by inversion from the switching pulses to the actual controllable switch.

[0056] Also, in the illustrations explained above, only a single LED chain has been consistently shown as a load. This is not a requirement of the invention, and the load can comprise various networks of LEDs and LED chains. The output voltage required of the buck converter is in each case the sum of voltage drops over the largest number of individual LEDs that together form a current path across the output of the buck converter.

[0057] Principles according to embodiments of the invention can be applied also in cases where there are multiple buck converters that all receive their input voltages from a common controllable first power source. In such a case it may happen that different numbers of serially coupled LEDs are driven by different ones of the buck converters, so if each of them produces an indication signal indicative of the difference between its own input and output voltages, the controllable first power source may receive conflicting indications. In such a case it is most advantageous to control the controllable first power source according to the indication signal asking for the highest voltage, in order to ensure that all buck converters receive enough electric energy from the controllable first power source.

[0058] Another class of variations involves the way in which the current measurements are made, or more generally, how the generation of switching pulses in the buck converter is implemented. Current hysteresis control based on measuring the current during both the conducting and non-conducting periods is only one alternative. For example in the embodiment illustrated in fig. 11, it would be possible to move the current sensing resistor from its indicated location to between the controllable switch 105 and the negative output node of the switched-mode power supply, or between the cathode of the diode 108 and the positive output node of the switched-mode power supply. In such a case the current sensing resistor would be out of the inner loop of the buck converter, and consequently only measure the current during the conducting periods of the controllable switch 105. Since the length of the non-conducting period is a function of only the output voltage of the buck converter, it is easy to time the beginning of the next switching pulse by applying a non-conducting period of calculated length (taken that the circuit element that forms the switching pulses is made conscious of the present output voltage, for example with a connection from the voltage divider 1101).

[0059] Yet another class of variations involves the way in which the required output voltage of the buck converter is found out. As an example, the standardisation of LED lighting devices may advance to a point where a connector of a LED-based load comprises a machine-readable indication of the required load voltage. In such a case the driver device according to an embodiment of the invention may comprise a reader unit configured to read the required load voltage from the connector and use it to form the indication signal.

Claims

1. A driver device for light-emitting diodes, comprising:

- a controllable first power source configured to produce a first voltage at its output, the magnitude of said first voltage being dependent on a control signal, and
- a buck converter having an input coupled to the output of said first power source, and an output for coupling light-emitting diodes thereto;

characterised in that the driver device comprises:

- a load voltage indicator configured to produce an indication signal dependent on a load voltage required by a load coupled to the output of said buck converter, and
- a feedback coupling configured to couple said indication signal as a control signal to said controllable first power source.

2. A driver device according to claim 1, **characterised in that** it comprises:

- a comparator configured to compare a voltage difference between the input of the buck converter and the output of the buck converter to a target value and to produce said indication signal as an indication of how much said voltage difference differs from said target value.

3. A driver device according to any of claims 1 or 2, **characterised in that** said buck converter comprises:

- a controllable switch that has a conducting state, in which the controllable switch is configured to conduct electric current from said output of said first power source, and a non-conducting state,
- an LC circuit that comprises an inductor, a capacitor, and a flywheel switch, and that is configured to receive electric current through said controllable switch into said inductor during a conducting state of said controllable switch, and to deliver current from said inductor into a loop comprising said inductor, said flywheel switch, and a load coupled to an output of said buck converter, during a non-conducting state of said controllable switch, and
- a control circuit configured to repeatedly change the state of said controllable switch between conducting and non-conducting states based on a measured momentary current through the buck converter.

4. A driver device according to any preceding claim, **characterised in that** the configured effect of said feedback coupling is to control the output voltage of said controllable first power source so that said voltage difference remains within predetermined limits of a constant, and preferably equal to said constant.

5. A driver device according to any preceding claim, **characterised in that** said first power source is a switched-mode power supply, a duty cycle of which is configured to be proportional to the value of said indication signal.

6. A driver device according to claim 5, **characterised in that**:

- said switched-mode power supply comprises a transformer that divides the switched-mode power supply to a primary side and a secondary side with galvanic isolation between the primary and secondary sides,
- the driver device comprises a galvanically isolating signal transmitter for conveying said indication signal to the primary side of said switched-mode power supply.

7. A driver device according to any previous claim, **characterised in that**:

- said buck converter comprises a control input for receiving on and off commands,
- the driver device comprises a control unit with an output coupled to said control input of said buck converter,
- said control unit is configured to repeatedly issue on and off commands to said buck converter through said control input in response to external commands indicative of desired lighting intensity, a pulse frequency of said on and off commands being higher than 100 Hz and lower than a switching frequency of said buck converter.

8. A driver device according to claim 7, **characterised in that** said control unit is implemented within a common integrated circuit with said comparator.

9. A driver device according to claim 8, **characterised in that** said common integrated circuit additionally includes the a control circuit of the buck converter, which is configured to repeatedly change the state of the controllable switch in the buck converter between conducting and non-conducting states based on a measured momentary current through the buck converter.

10. A method for providing electricity to light-emitting diodes, comprising:

- producing a first voltage, and
- using a buck converter to convert said first voltage into an output voltage that is coupled across a chain of said light-emitting diodes;

characterised in that the method comprises:

- producing an indication signal depending on a load voltage required by a load coupled to an output of said buck converter, and
- using said indication signal to control the magnitude of the first voltage.

11. A method according to claim 10, **characterised in that** the method comprises:

- comparing a voltage difference between the input of the buck converter and the output of the buck converter to a target value,
- producing said indication signal as an indication of how much said voltage difference differs from said target value.

12. A method according to any of claims 10 or 11, **characterised in that** the method comprises:

- controlling the magnitude of said first voltage so that said voltage difference remains within predetermined limits of a constant, and preferably equal to said constant.

13. A method according to any of claims 10 to 12, **characterised in that** the method comprises:

- using a switched-mode power supply to produce said first voltage, and
- making a duty cycle of said switched-mode power supply proportional to a value of said indication signal.

14. A method according to any of claims 10 to 13, **characterised in that** the method comprises:

- repeatedly switching the buck converter on and off at a frequency that is higher than 100 Hz but lower than a switching frequency of the buck converter, in order to control a lighting intensity of said light-emitting diodes.

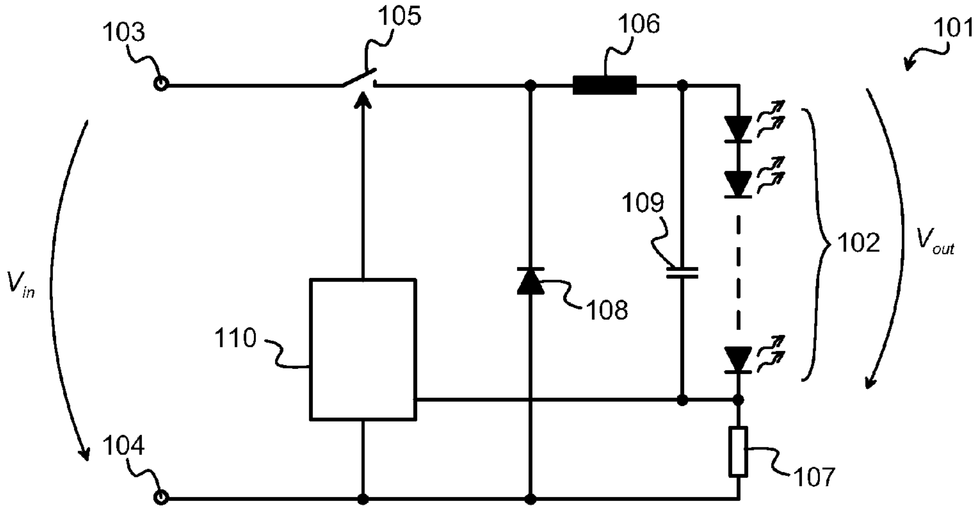


Fig.1
PRIOR ART

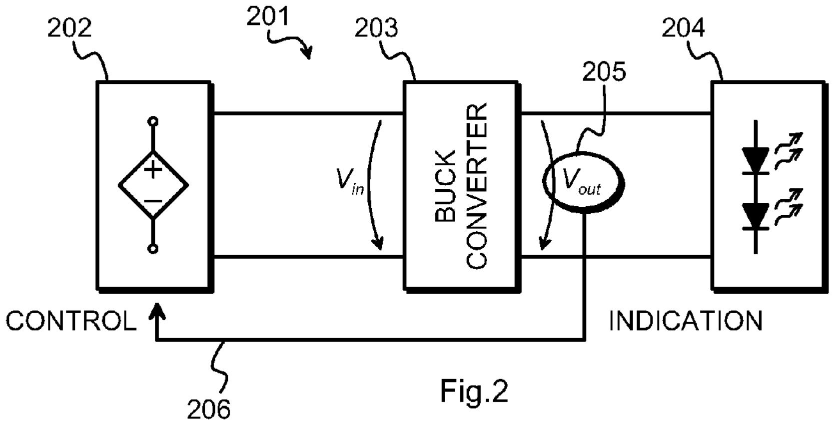


Fig.2

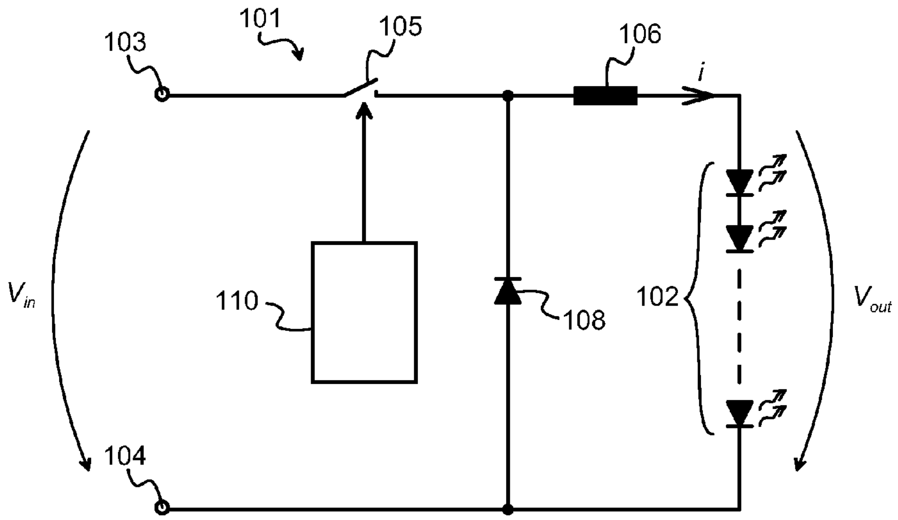


Fig.3

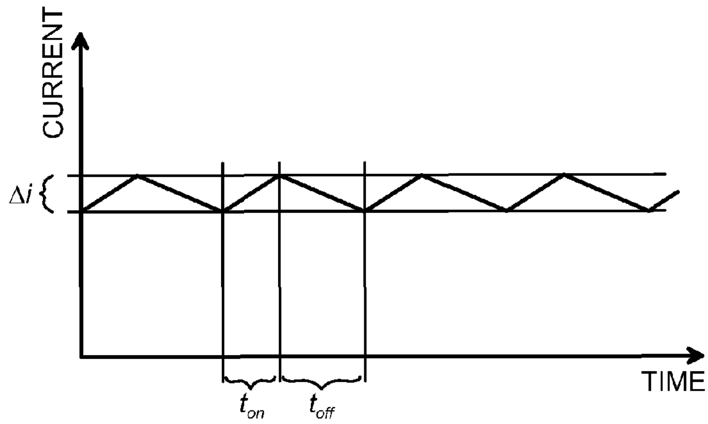


Fig.4

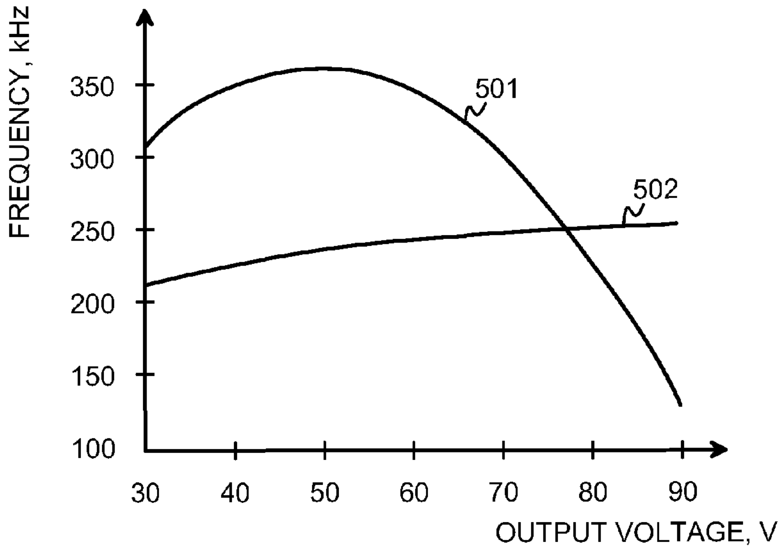


Fig.5

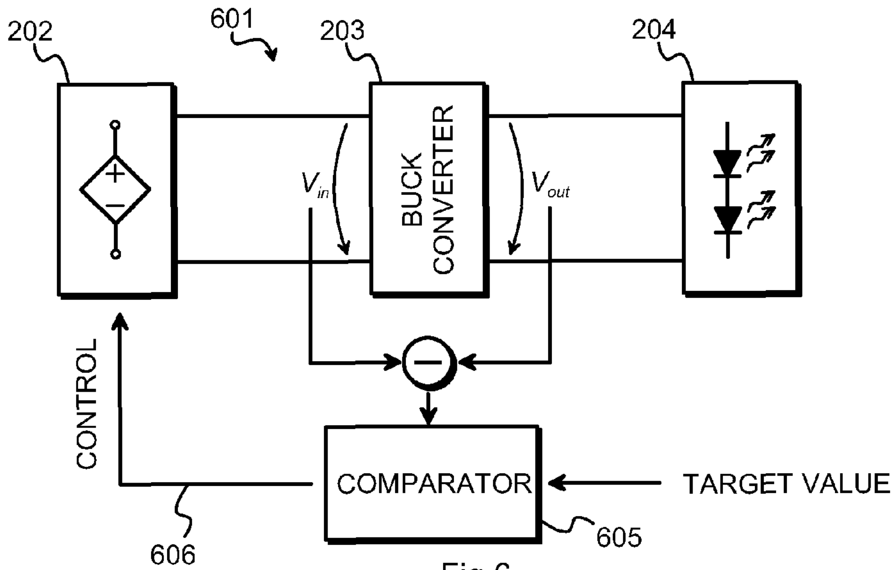


Fig.6

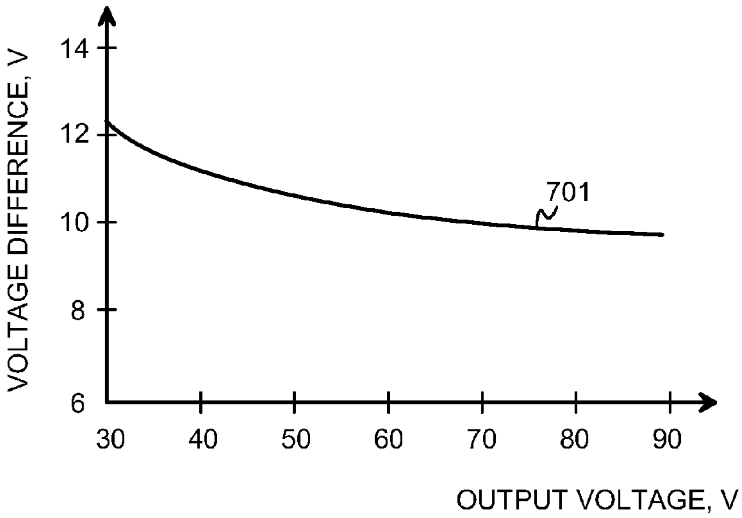
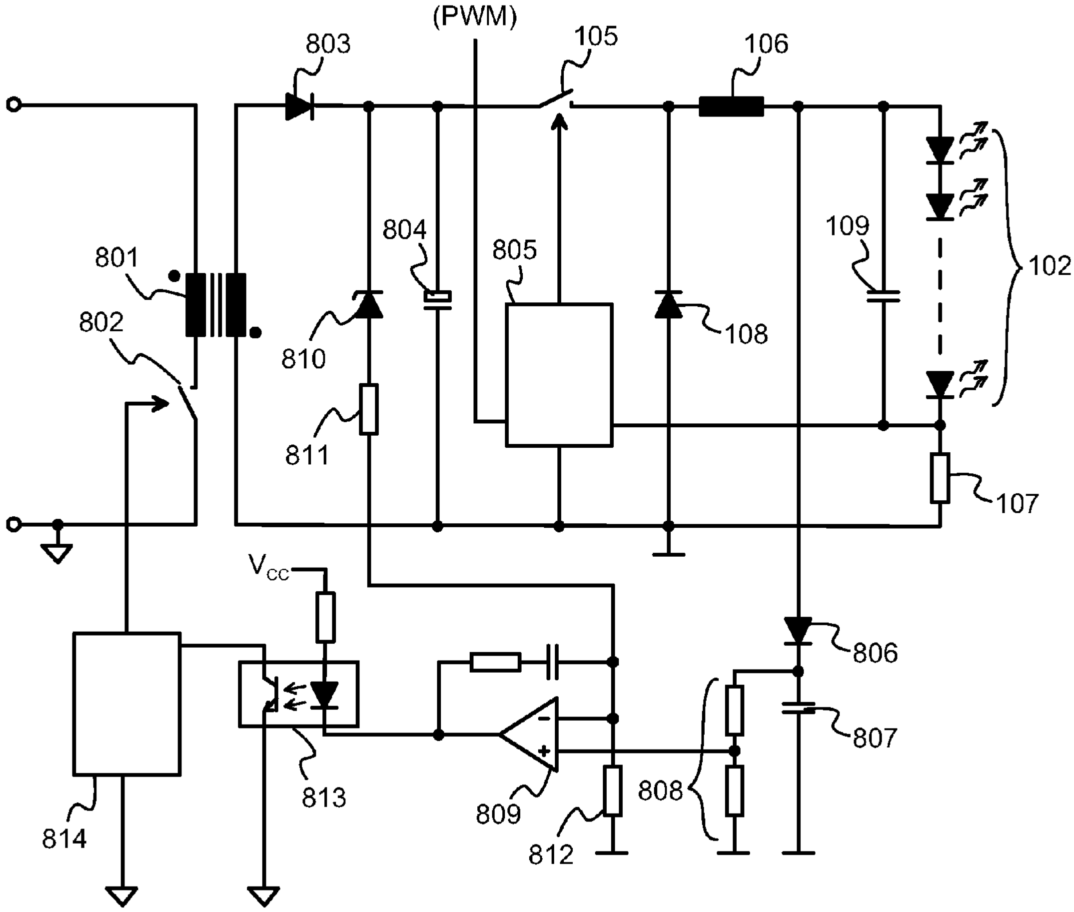

14
12
10
8
6
VOLTAGE DIFFERENCE, V
701
30
40
50
60
70
80
90
OUTPUT VOLTAGE, V

Fig.7


(PWM)
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105
106
804
805
109
102
801
802
810
108
811
107
VCC
806
807
813
809
808
814
812

Fig.8

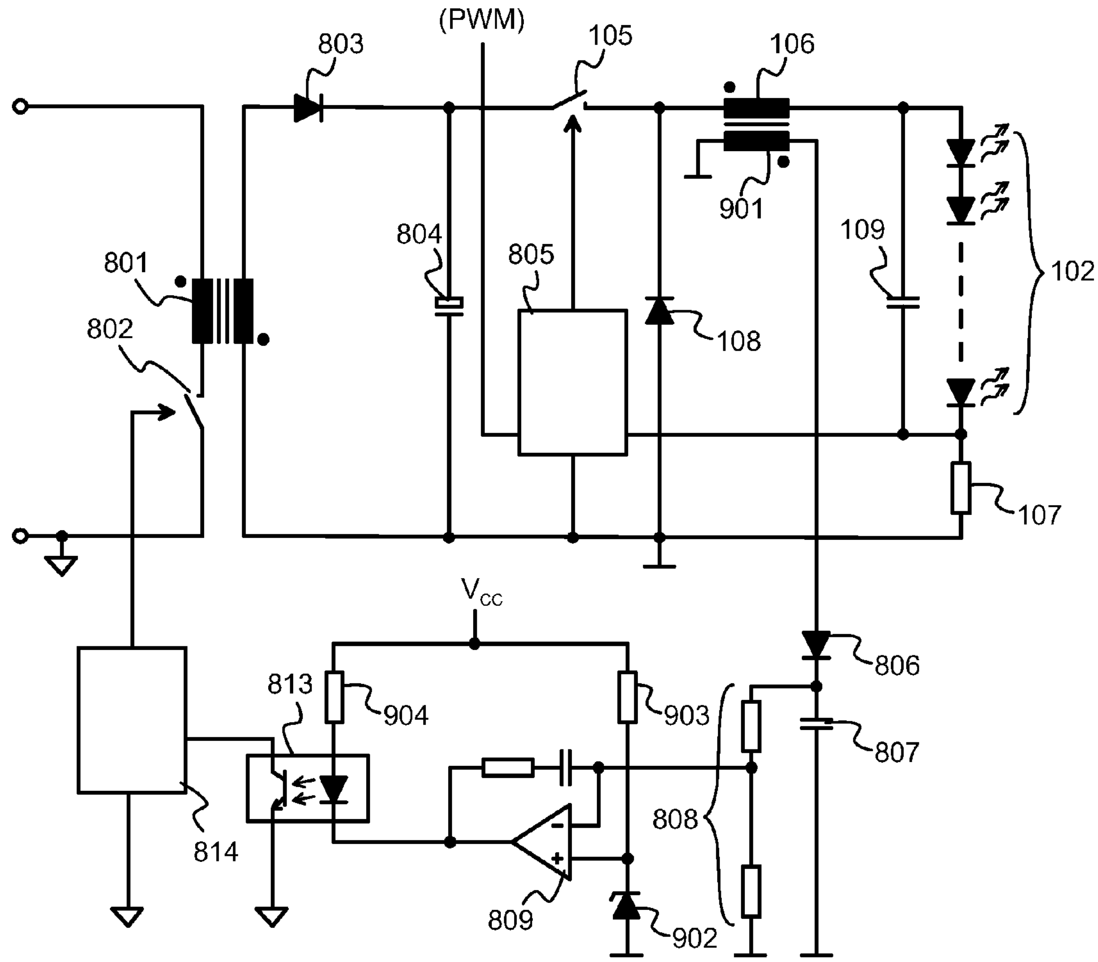
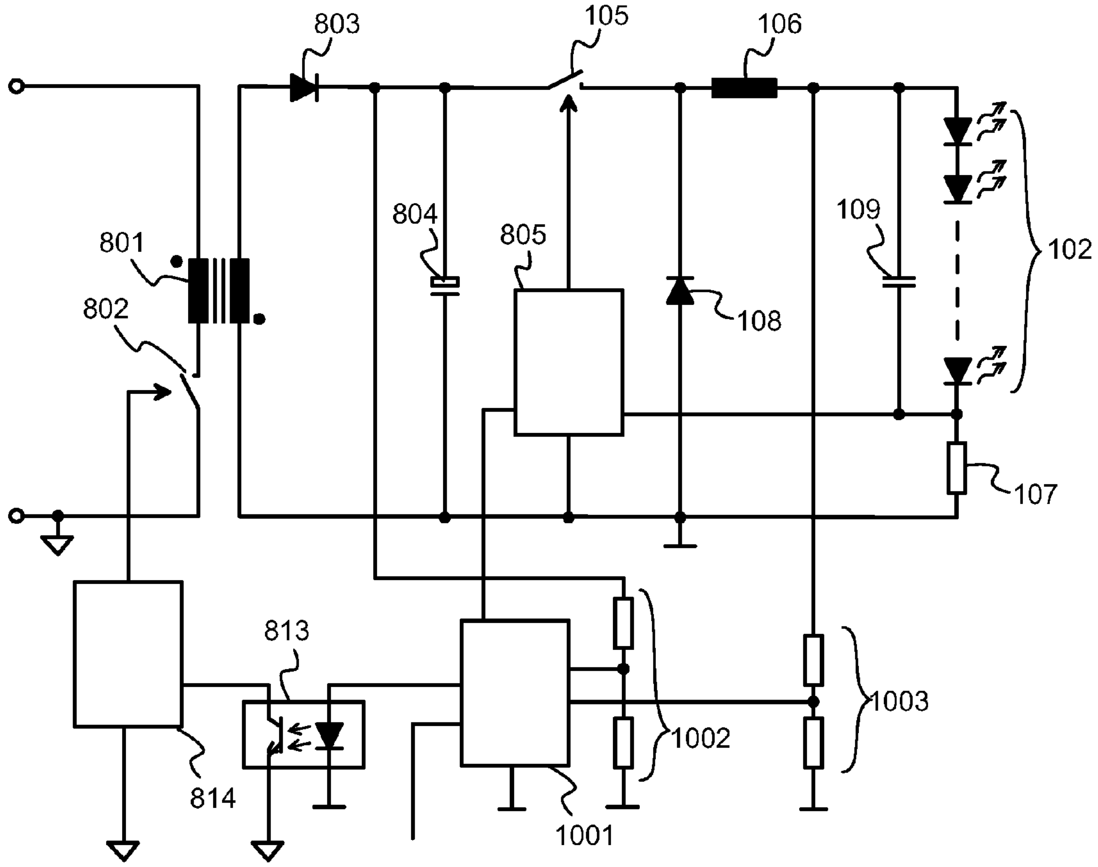

(PWM)
803
105
106
901
804
805
801
802
109
102
108
107
V_{CC}
806
813
904
903
807
808
814
809
902

Fig.9



803
105
106
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109
102
801
802
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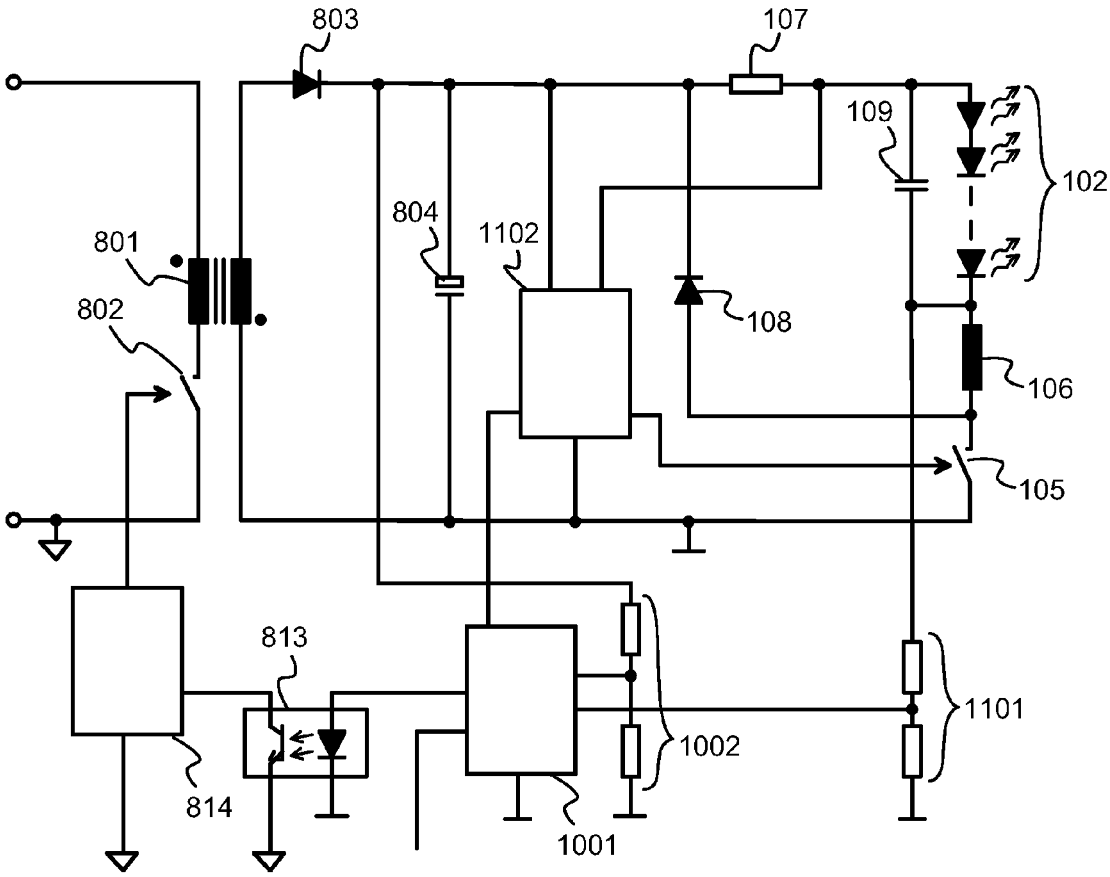
107
813
1003
1002
814
1001

Fig.10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1102
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813
1101
1002
814
1001

Fig.11

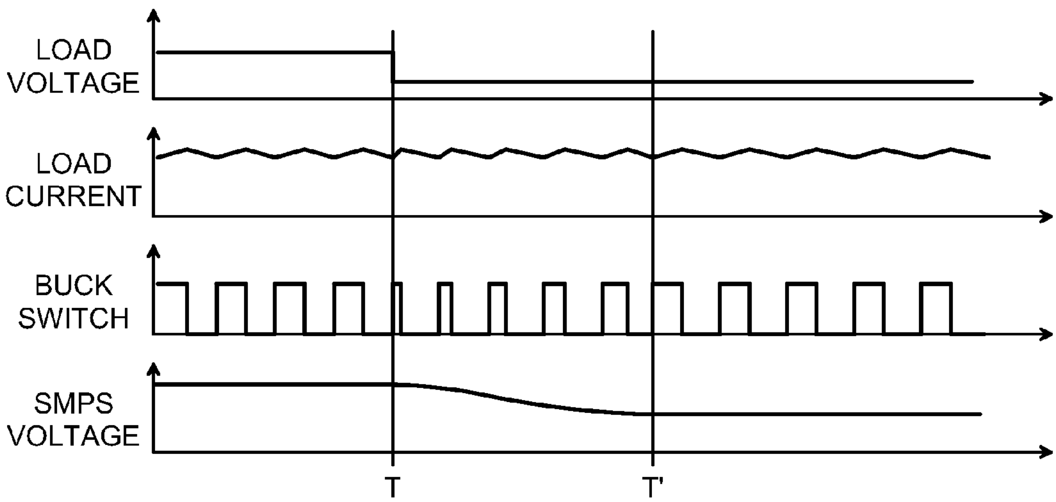
LOAD
VOLTAGE
LOAD
CURRENT
BUCK
SWITCH
SMPS
VOLTAGE
T
T'

Fig.12

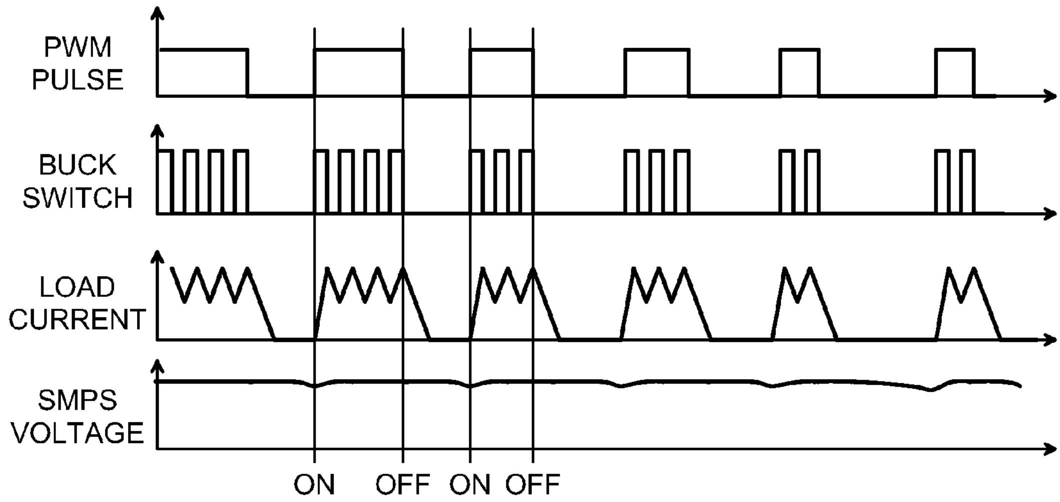
PWM
PULSE
BUCK
SWITCH
LOAD
CURRENT
SMPS
VOLTAGE
ON
OFF
ON
OFF

Fig.13

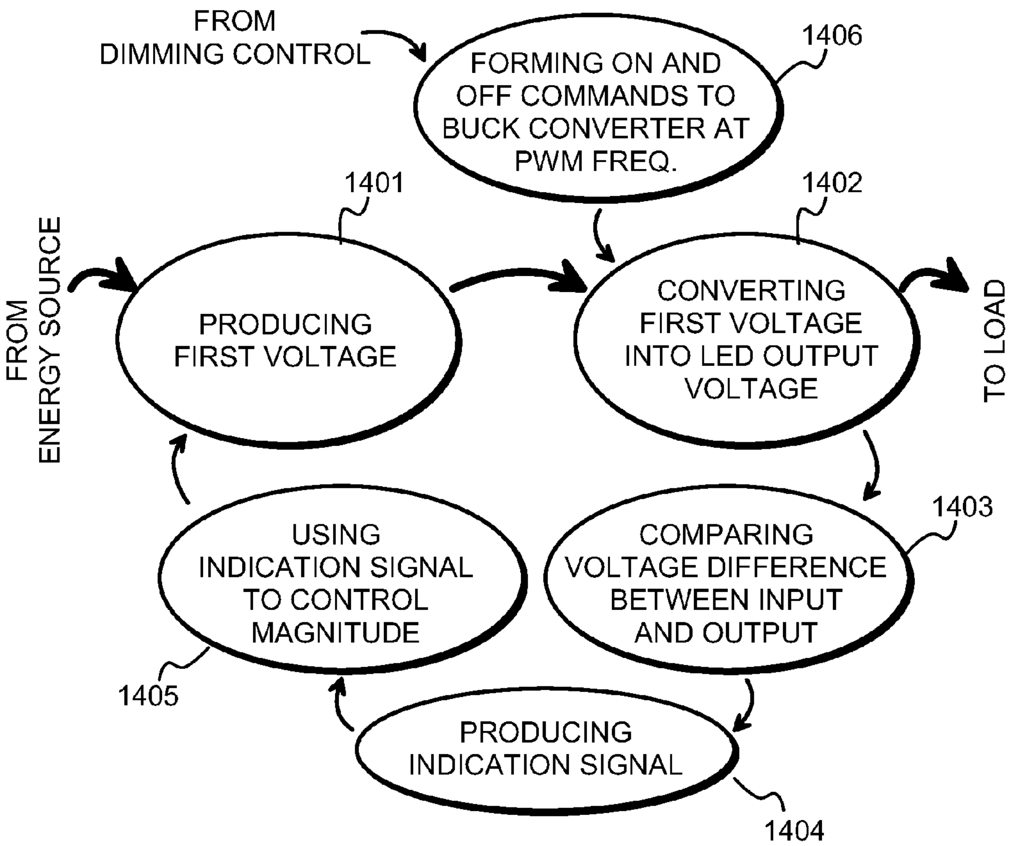
FROM
DIMMING CONTROL
FORMING ON AND
OFF COMMANDS TO
BUCK CONVERTER AT
PWM FREQ.
1406
1401
1402
FROM
ENERGY SOURCE
PRODUCING
FIRST VOLTAGE
CONVERTING
FIRST VOLTAGE
INTO LED OUTPUT
VOLTAGE
TO LOAD
1403
USING
INDICATION SIGNAL
TO CONTROL
MAGNITUDE
COMPARING
VOLTAGE DIFFERENCE
BETWEEN INPUT
AND OUTPUT
1405
PRODUCING
INDICATION SIGNAL
1404

Fig.14

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EUROPEAN SEARCH REPORT

Application Number
EP 11 17 0654

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	WO 2010/005291 A1 (ELDOLAB HOLDING B V [NL]; WELTEN PETRUS JOHANNES MARIA [NL]) 14 January 2010 (2010-01-14) * the whole document * -----	1-14	INV. H05B33/08
A	US 2010/026208 A1 (SHTEYNBERG ANATOLY [US] ET AL) 4 February 2010 (2010-02-04) * page 1, paragraph 1 - page 7, paragraph 61; figures 1-4 * -----	1-14	
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A	US 2009/237007 A1 (LENG CHUNG-MING [TW]) 24 September 2009 (2009-09-24) * the whole document * -----	1-14	

TECHNICAL FIELDS SEARCHED (IPC)

H05B

The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
Munich	7 November 2011	Burchielli, M

CATEGORY OF CITED DOCUMENTS

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E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 11 17 0654

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07-11-2011

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