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(54) **Dimmable LED driver, and method for producing a dimming signal**

(57) A driver device provides variable electric current to at least one semiconductor light-emitting device. It comprises a switched-mode power supply with a current switch for generating an output current of the driver device, and a switch driver circuit (202) to provide switching pulses to said current switch (201) at a switching frequency. The switch driver circuit (202) responds to voltages exceeding a first threshold at a control input (EN/DIM) by enabling the providing of switching pulses. It responds to voltages between said first threshold and a second, further threshold by allowing an amplitude of a measured current to reach a value proportional to the voltage at the control input. A control pulse formatter (203) provides the control input (EN/DIM) with control pulses of variable amplitude exceeding said first threshold at a pulse width modulation frequency smaller than said switching frequency.

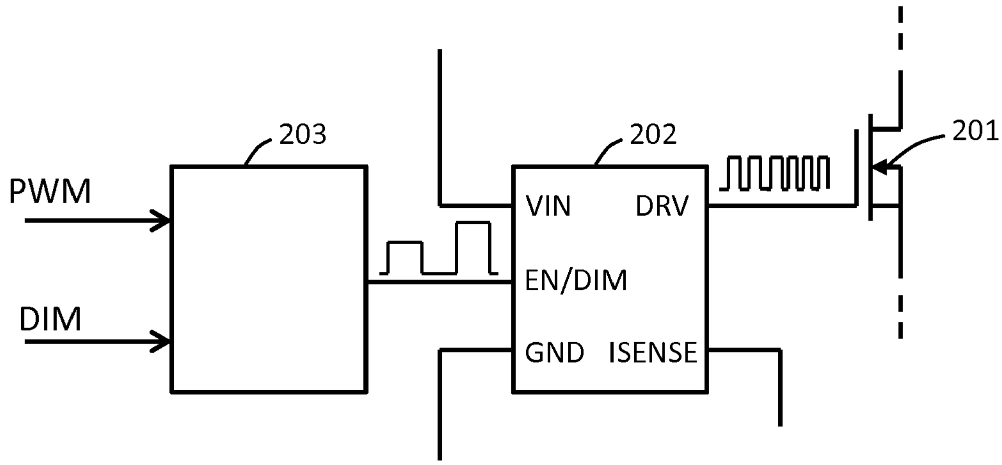


Fig. 2

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## Description

### FIELD OF THE INVENTION

**[0001]** The invention concerns the field of making a variable electric current flow through semiconductor light-emitting devices, with the result of varying the amount of produced light. In particular the invention concerns the way in which a processor or other controlling circuit communicates the desired brightness level to the switched-mode power supply that acts as an output stage of the driver of the semiconductor light-emitting devices.

### BACKGROUND

**[0002]** This description uses the acronym LED (Light-Emitting Diode) to refer to all kinds of semiconductor light-emitting devices that are or can be driven with pulsating electric current. Non-limiting examples of LEDs are white LEDs, coloured LEDs, ultraviolet LEDs, infrared LEDs, laser diodes, and polychromatic LEDs.

**[0003]** Two basic approaches to LED dimming are PWM (Pulse Width Modulation) dimming and analog dimming, of which the latter may also be called linear dimming or amplitude dimming. Basic analog dimming involves making a continuous electric current flow through the LEDs and varying its magnitude. Basic PWM dimming involves making a pulsating current of constant amplitude flow through the LEDs and varying the duty cycle of the pulses. Combining the two basic approaches results in so-called hybrid dimming, in which both the duty cycle and the amplitude of the current pulses through the LEDs may change. A large number of hybrid dimming strategies are known: the LED driver may for example apply only analog dimming near the brightest end of desired light intensities and begin chopping the current at decreasing duty cycles only at the dimmest intensities. Another well-known strategy is to decrease the current amplitude in steps and to add PWM so that the duty cycle changes abruptly between current steps and continuously within each step.

**[0004]** A typical LED driver includes a switched-mode power supply, such as a buck converter, as its output stage. When enabled, a switch driver circuit in the buck converter produces switching pulses at a relatively high frequency such as tens or hundreds of kHz. The switching pulses drive a MOSFET or a corresponding solid-state switch that alternatingly stores energy to the magnetic field of an inductor and discharges energy therefrom to make an electric current flow through the LEDs. A current feedback control arrangement measures the electric current through the LEDs and maintains it at an appropriate value in accordance with an analog dimming control signal. The buck converter is repeatedly enabled and disabled at a significantly lower frequency, such as only some hundreds or thousands of Hz. A PWM dimming control signal defines the duty cycle of such enabling and disabling.

**[0005]** The analog dimming control signal and the PWM dimming control signal come to the buck converter (or other type of switched-mode power supply) from a processor or other controlling circuit that constitutes a part of the LED driver. The PWM dimming control signal is typically a square-wave-type digital signal, i.e. one that toggles between a logical "high" or "1" level and a logical "low" or "0" level with a frequency and duty cycle equal to those desired of the pulse-width-modulated LED current, so that the PWM dimming control signal can be directly coupled to an ENABLE pin of the switch driver to effect PWM dimming. The analog dimming control signal may be for example an analog voltage level that is made to interact with a current feedback control loop built around and employed by the switch driver. Such interacting changes e.g. a scaling factor that the current feedback control loop uses in taking a sample of the LED current.

**[0006]** In order to best fit the needs of mass production a circuit used for hybrid dimming should be simple and reliable, and possible to realize with a relatively small number of relatively cheap components. It should be robust against individual variations in component performance, and it should enable using simple and reliable software routines in the processor that forms the control signals.

### SUMMARY

**[0007]** It is an objective of the present invention to provide a method and devices for providing variable electric current to at least one semiconductor light-emitting device with a simple and robust circuit arrangement that is easily adaptable to a number of driver configurations.

**[0008]** The objectives of the invention are reached with a method and driver device as defined by the respective independent claims.

**[0009]** According to an example embodiment, a driver device is provided for providing variable electric current to at least one semiconductor light-emitting device. The driver device comprises:

- a switched-mode power supply for generating an output current of the driver device, the switched-mode power supply comprising a current switch,
- a switch driver circuit configured to provide switching pulses to said current switch at a switching frequency,
- a control input of said switch driver circuit, wherein said switch driver circuit is configured to respond to voltages greater than a first threshold at said control input by enabling said providing of switching pulses and to voltages between said first threshold and a second, higher threshold at said control input by allowing an amplitude of a measured current to reach a value proportional to the voltage at said control

input, and

- a control pulse formatter coupled to said control input and configured to provide said control input with control pulses of variable amplitude above said first threshold at a pulse width modulation frequency smaller than said switching frequency.

**[0010]** According to another example embodiment, a method is provided for providing variable electric current to at least one semiconductor light-emitting device. The method comprises:

- forming control pulses of variable amplitude and duty cycle,

- conducting said control pulses to a control input of a switch driver circuit, wherein said switch driver circuit responds to voltages greater than a first threshold at said control input by enabling the providing of switching pulses to the current switch of a switched-mode power supply, and to voltages between said first threshold and a second, higher threshold at said control input by allowing an amplitude of a measured current to reach a value proportional to the voltage at said control input, and

- using the output current of said switched-mode power supply to provide said variable electric current.

**[0011]** The exemplifying 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" and its derivatives are used in this patent application as an open limitation that does not exclude the existence of also unrecited features. The features described hereinafter are mutually freely combinable unless explicitly stated otherwise.

**[0012]** 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 detailed description of specific embodiments when read in connection with the accompanying drawings.

## BRIEF DESCRIPTION OF DRAWINGS

**[0013]**

Fig. 1 illustrates an SMPS driving LEDs with variable current,

fig. 2 illustrates a driver device with PWM and analog control,

fig. 3 illustrates a switch driver circuit that accepts PWM and analog control,

fig. 4 illustrates an SMPS suitable for driving LEDs with variable current,

fig. 5 illustrates a double buffer arrangement for combining PWM and analog control,

fig. 6 illustrates an exemplary embodiment of a double buffer arrangement,

fig. 7 illustrates a driver device,

fig. 8 illustrates control pulses of variable amplitude and duty cycle,

fig. 9 illustrates control pulses of variable amplitude and duty cycle,

fig. 10 illustrates control pulses of variable amplitude and duty cycle,

fig. 11 illustrates control pulses of variable amplitude and duty cycle,

fig. 12 illustrates a driver device, and

fig. 13 illustrates an SMPS suitable for driving LEDs with variable current.

## DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

**[0014]** Fig. 1 illustrates the use of a switched-mode power supply 101 for generating an output current that in turn can be conducted as a variable output current $I_{LED}$ to at least one semiconductor light-emitting device. In the following description the acronym LED is used to generally designate all kinds of semiconductor light-emitting devices. Four LEDs 102 are shown fig. 1 coupled as a LED chain across the output of the switched-mode power supply 101.

**[0015]** A switched-mode power supply or SMPS is a device that converts electric power by repeatedly switching on and off a current that at least partly flows through an inductive component. Energy is alternatingly stored into the magnetic field of the inductive component and discharged therefrom, with suitable rectification and filtering circuits smoothing the output voltage and current. At the time of writing this description the most common SMPS topology used as the output stage of LED drivers is the buck converter, but the invention is not limited to the use of buck converters but covers all kinds of switched-mode power supplies that accept both analog and PWM control, which are schematically shown as the DIM and PWM inputs respectively in fig. 1. The input voltage to the SMPS may come from a previous stage in the driver device, and appears between the Vbus and 0V nodes shown in fig. 1. The variable output current $I_{LED}$ may be directly the output current of the SMPS, or it may some derivative thereof for example after some filtering or additional switching.

**[0016]** If follows from the definition of a switched-mode power supply that it comprises a current switch on a main current path that conducts the decisive portion of electric current flowing through the SMPS. A MOSFET (metal oxide semiconductor field effect transistor) is frequently used as the current switch due to its advantageous switching properties, but also other kinds of solid-state switches can be used. The current switch is operated with a switch driver circuit that is configured to provide switching pulses to the current switch at a switching frequency. If a MOSFET is used as the switch, the switching pulses are voltage pulses coupled to its gate. The MOSFET is used as an on/off switch, meaning that each switching pulse turns it into completely conductive state and between switching pulses it is completely non-conductive. Major requirements for the switch driver circuit are the ability to provide switching pulses of sufficiently large amplitude to turn the MOSFET (or other current switch) into saturation mode, and the ability to maintain the edges of switching pulses steep in order to minimize switching losses. LED drivers typically use purpose-built integrated circuits as switch driver circuits, possibly augmented with some external discrete components.

**[0017]** Fig. 2 shows a special case of a current switch 201 and a switch driver circuit 202 configured to provide switching pulses to the current switch 201 at a switching frequency. The location of the current switch 201 on a main current path of a switched-mode power supply is schematically illustrated with the connections shown with dashed lines. Five connections to or from the switch driver circuit 202 are shown. A VIN connection is an operating voltage input, and a GND connection is a connection to a fixed reference potential such as the local ground potential. A DRV connection is the output connection for the switching pulses. An ISENSE connection represents a feedback connection, through which the switch driver circuit 202 may receive feedback quantities that represent e.g. a measured current somewhere along the main current path.

**[0018]** The arrangement of fig. 2 is special because of the connection labeled EN/DIM in fig. 2, which is a control input of the switch driver circuit 202. It has dual functions. On one hand, the switch driver circuit 202 is configured to respond to voltages exceeding a first threshold at the control input EN/DIM by enabling the providing of switching pulses to the current switch 201. In other words, the control input acts as an enabling input: if a voltage not exceeding said first threshold appears at the control input, no switching pulses are allowed to be provided to the current switch 201. The voltage at the control input must exceed the first threshold in order to enable the switch driver circuit 202, i.e. to allow the provision of switching pulses to the current switch 201. On the other hand the switch driver circuit 202 is configured to respond to voltages between the first threshold and a second, further threshold at the control input EN/DIM by allowing an amplitude of a measured current to reach a value proportional to the voltage at said control input. The measured current refers here to a current, the measurement of which produces a feedback value to the connection named ISENSE in fig. 2. Speaking of a voltage at a single node, like at a control input for example, means that the voltage between that node and a reference potential (such as the local ground potential) is meant.

**[0019]** Fig. 3 illustrates an example of a circuit that can be used as the switch driver circuit 202. An input voltage is coupled to the VIN input, and an internal reference voltage generator 301 uses it to generate a fixed internal reference voltage. A scaled sample of this internal reference voltage is taken to the inverting input of a comparator 302. This scaled sample constitutes the first threshold. The voltage at the control input labeled EN/DIM is coupled to the non-inverting input of the comparator 302. If the EN/DIM input is low, i.e. if the voltage at the control input does not exceed the first threshold, the output of the comparator 302 is low and inhibits the operation of a switching pulse formation block 303. Correspondingly if the voltage at the control input EN/DIM exceeds the first threshold, the output of the comparator 302 is high and enables the operation of the switching pulse formation block 303.

**[0020]** For measuring a current with a circuit like that in fig. 3, the potential difference between the VIN and ISENSE inputs is decisive. We may assume that lines to these inputs come from opposite sides of a current sensing resistor (not shown in fig. 3). Each of the inputs is coupled, through a respective coupling resistor, to the corresponding input of a current sensing comparator 304. A high output of the current sensing comparator 304 coincides with an active switching pulse to the current switch (i.e. high value at the DRV output). At that time the resistor 305 is shorted, and of the two resistors 305 and 306 only the latter takes part in the current measurement, defining a value that the measured current is allowed to reach. When the measured current reaches that value, the potential difference between the VIN and ISENSE inputs becomes large enough to switch the output of the current sensing comparator 304 low. This terminates the present switching pulse in the switching pulse formation block 303, and also makes the resistor 305 take part in the current measurement. As the measured current declines, the potential difference between the VIN and ISENSE inputs decreases until it reaches a minimum value at which the output of the current sensing comparator 304 goes high again, initiating the next switching pulse in the switching pulse formation block 303 and again shorting the resistor 305.

**[0021]** Thus by alternatingly omitting and including the resistor 305 in the current measurement a kind of current hysteresis control is achieved. As long as the voltage at the control input EN/DIM exceeds the first threshold but does not exceed a second, further threshold, the transistor 307 is operated in linear mode, so that also its ohmic resistance is included in the current measurement. This has the effect of allowing an amplitude of the measured current to reach a value that is proportional to the voltage at the control input EN/DIM. After the voltage at the control input EN/DIM exceeds even the second threshold, the allowed amplitude of the measured current does not increase anymore, because the transistor 307 is in saturation mode.

**[0022]** Saying that the amplitude of the measured current is allowed to reach a value that is proportional to the voltage at the control input EN/DIM does not require proportionality according to the strictly mathematical definition of the term. Merely it is meant that the more the voltage at the control input EN/DIM exceeds the first threshold, the larger the amplitude of the measured current is allowed to become, until the voltage at the control input EN/DIM reaches or exceeds the second threshold. The exact nature of the proportionality, as well as the value of the second threshold, depend on many factors such as the output value of the internal reference voltage generator 301; the gain characteristics of the amplifier 308 used to drive the transistor 307; the conductivity characteristics of the transistor 307; and the resistance of resistors 305 and 306.

**[0023]** Also when it is said that the voltage at the control input EN/DIM exceeds a threshold, it does not necessarily mean that the voltage between the control input EN/DIM and the local ground potential becomes larger than a threshold value. It is also possible that the voltage between the control input EN/DIM and the local ground potential is relatively large to start with, so that exceeding a threshold means that said voltage becomes smaller than the threshold value. The way in which the concept of exceeding is defined naturally has an effect on e.g. how the input polarities of the various comparators in the driver circuit must be selected.

**[0024]** The switch driver circuit 202 may be an integrated circuit, and the control input EN/DIM may be an input pin of such an integrated circuit. For example the circuit MP24894 of Monolithic Power Systems, San Jose, California has a control input of the kind explained above, although the manufacturer has not come up with the idea of using the control input simultaneously for both PWM and analog control, but only for one of them at a time. In the MP24894 the value of the first threshold is 0.3 V, and the value of the second threshold is 2.7 V. As an alternative the switch driver circuit 202 may be built of discrete components, for example following the block diagram shown in fig. 3 and the explanations given above of its various functional blocks. Also other basic approaches to the topology and design of the circuit are possible, as long as it can be made to react to the values at the control input in the way that has been explained above.

**[0025]** Fig. 4 illustrates a switched-mode power supply that uses a switch driver circuit 401 with a pin configuration and internal operation similar to those of the MP24894. The main current path goes from a first input voltage node Vbus through a current sensing resistor 402 to the first output voltage node LED+, and from the second output voltage node LED- through an inductor 403 and a current switch 404 to the second input voltage node 0V. A freewheeling current path goes through the current sensing resistor 402 to the first output voltage node LED+, and from the second output voltage node LED- through the inductor 403 and a diode 405 back to the first end of the current sensing resistor 402. An input capacitor 406 is coupled between the first and second input voltage nodes, and an output capacitor 407 is coupled between the first and second output voltage nodes.

**[0026]** Couplings to the VIN and ISENSE inputs of the switch driver circuit 401 come from opposite ends of the current sensing resistor 402, and the DRV output of the switch driver circuit 401 is coupled to the gate of the MOSFET that acts as a current switch 404. The switch driver circuit 401 is configured to respond to voltages between first and second thresholds at its control input EN/DIM by allowing a potential difference across the current sensing resistor 402 to reach a value proportional to the voltage at the control input EN/DIM during each switching pulse.

**[0027]** Couplings from the VCC and GND connections of the switch driver circuit 401 are to the local ground potential (the 0V line), through a capacitor 408 from the first-mentioned and directly from the last-mentioned. The node that offers a coupling to the EN/DIM input of the switch driver circuit 401 is marked with the reference designator 409.

**[0028]** A reference is made back to fig. 2 for considering how control pulses are formatted for coupling to the control input EN/DIM of the switch driver circuit. The arrangement of fig. 2 comprises a control pulse formatter 203 that is coupled to the control input EN/DIM of the switch driver circuit 202. The control pulse formatter 203 is configured to provide the control input EN/DIM with control pulses of variable amplitude that exceeds the first threshold at a pulse width modulation frequency smaller than the switching frequency. The difference in frequencies would typically be in the order of decades; the much smaller difference that is schematically illustrated in fig. 2 has been chosen only for graphical clarity.

**[0029]** Above it was pointed out that even if the amplitude of the control pulses may vary, also the smallest amplitude (i.e. the lowest voltage value) used for a control pulse exceeds the first threshold. Comparing to fig. 3, even the smallest amplitude used for a control pulse represents a voltage value large enough to turn the output of the amplifier 302 high, which in turn enables the operation of the switching pulse formation block 303. Thus each control pulse acts as an enabling pulse of the overall operation of the switch driver circuit 202. In other words, the control pulses act as PWM control pulses to the switch driver circuit 202 regardless of any variation in their amplitude. The frequency and duty cycle of the control pulses will directly determine the frequency and duty cycle of repeatedly enabling and disabling the switch driver circuit 202, and therethrough repeatedly enabling and disabling the whole switched-mode power supply that provides variable electric current to at least one LED.

**[0030]** The amplitude of each control pulse sets, control pulse by control pulse, the value that the amplitude of the measured current is allowed to reach during each of those switching pulses that occur in the switched-mode power supply during that particular control pulse. The relatively large difference in frequency between the control pulses and switching pulses means that during an individual control pulse there may occur tens, hundreds, or even thousands of switching pulses. It is even possible that the amplitude of the control pulse is not constant but changes during the control pulse, in which case the allowed value of the measured current may vary in a similar way in the switched-mode power supply during that control pulse.

**[0031]** The control pulse formatter 203 of fig. 2 acts as a kind of multiplexer, in the sense that it receives two input signals (PWM and DIM) and outputs a common output signal that has characteristics derived from both input signals: the frequency and duty cycle of the pulsed output signal may follow directly the frequency and duty cycle of the PWM input signal, and the amplitude of the pulses in the output signal may follow directly the amplitude of the DIM input signal. Direct following is not a requirement: the control pulse formatter 203 may also implement scaling and/or mapping functions that derive the frequency, duty cycle, and amplitude of the output signal on the basis of some unequivocal rule(s).

**[0032]** Fig. 5 illustrates schematically one possible approach to constructing a control pulse formatter 203. In this case both the PWM and DIM signals are assumed to come in the form of digital pulse trains, i.e. repeated regular transitions between two essentially fixed voltage levels, one of which is the "0" level and the other the "1" level. Since the voltage levels are fixed, the information content of a digital pulse train must come associated with some other characteristic of the pulse train. Such characteristics include but are not limited to the frequency and duty cycle of the pulse train.

**[0033]** The control pulse formatter 203 of fig. 5 comprises a first buffer 501 for receiving a first pulse train DIM, and a second buffer 502 for receiving a second pulse train PWM. The first buffer 501 is configured to form a control voltage, represented by line 503, depending on a characteristic of the first pulse train DIM. Said characteristic may comprise the frequency and/or duty cycle of the first pulse train DIM. The second buffer 502 is configured to chop the control voltage depending on pulses of the second pulse train PWM. Chopped lengths of the control voltage 503 constitute the control pulses that can be conducted for example to the control input EN/DIM of a switch driver circuit of the kind illustrated in fig. 2, 3, and/or 4. The amplitude of such control pulses vary according to the varying value of the voltage 503, originally determined by the frequency and/or duty cycle of the first pulse train DIM. The frequency and duty cycle of the control pulses are determined by the second pulse train PWM.

**[0034]** Fig. 6 illustrates an exemplary circuit topology that can be used to build a control pulse formatter of the kind described above with reference to fig. 5. The first buffer comprises an RC filter 601 followed by a buffer amplifier 602. The control voltage that is formed depending on a characteristic of the first pulse train appears at point 603. The second buffer comprises a buffer switch 604 that is operated by pulses of the second pulse train. The buffer switch 604 s coupled to alternatively block or pass the control voltage from point 603 to the output of the control pulse formatter, depending on the state of conduction of the buffer switch 604. In particular, when an "1" state occurs in the second pulse train, the lower switching transistor of the buffer switch 604 is conductive and the upper switching transistor is non-conductive, which allows the control voltage at point 603 to also appear at the output. When a "0" state occurs in the second pulse train, the lower switching transistor in the buffer switch 604 is non-conductive and the upper switching transistor is conductive, shorting the point 603 to the 0V line, which blocks the control voltage from passing to the output.

**[0035]** Fig. 7 illustrates a driver device for providing variable electric current to at least one semiconductor light-emitting device. It comprises a switched-mode power supply 701 for generating an output current of the driver device. The switched-mode power supply 701 may be called the output stage or second stage of the driver device, and it may be for example a buck converter of the kind shown in fig. 4. Although not shown in detail in fig. 7, the switched-mode power supply 701 comprises a current switch and a switch driver circuit configured to provide switching pulses to the current switch at a switching frequency.

**[0036]** The electric energy comes to the driver device from the upper left through a filter and rectifier block 702 and a so-called first stage switched-mode power supply 703, which may implement power factor correction and which is configured to produce the so-called bus voltage that is commonly referred to as Vbus. The bus voltage may come directly from the first stage to the second stage, or it may come through a separation transformer 704 that is shown separately in fig. 7 although it may be functionally part of the first stage switched-mode power supply 703. The primary side of the driver device may comprise a first stage controller 705 for controlling the operation of the first stage switched-mode power supply 703.

**[0037]** The switch driver circuit in the second stage switched-mode power supply 701 comprises a control input. The switch driver circuit is configured to respond to voltages exceeding a first threshold at said control input by enabling the providing of switching pulses. The switch driver circuit is also configured to respond to voltages between said first threshold and a second, further threshold at said control input by allowing an amplitude of a measured current to reach a value proportional to the voltage at said control input. A control pulse formatter 706 is coupled to said control input and configured to provide said control input with control pulses of variable amplitude exceeding said first threshold at a pulse width modulation frequency smaller than said switching frequency. The control pulse formatter 706 may be of the kind described above with reference to figs. 5 and 6. Comparing particularly to fig. 6, the VCC and 0V lines to the control pulse formatter 706 may come from the separation transformer 704, while the DIM and PWM lines to the control pulse formatter may come from a second stage controller 707, which may be for example a processor or microcontroller.

**[0038]** A processor used as the second stage controller 707 may comprise a first output and a second output, and be configured to provide a first pulse train (compare to DIM in figs. 5 and 6) at said first output and a second pulse train (compare to PWM in figs. 5 and 6) at said second output. This way both analog control and PWM control may be implemented with only digital one-pin outputs from the controlling processor: one digital output pin for analog control and one for PWM. The processor does not need to comprise any analog outputs for this purpose, and the program that the processor executes does not need to take into account the production of any analog values. If any changes need to be made to the frequencies and/or duty cycles and/or other characteristics of the pulse trains that carry the DIM and PWM signals, for example if a different switch driver circuit or different control pulse formatter is taken into use, it is relatively straightforward to make such changes by reprogramming the processor.

**[0039]** Fig. 7 also shows a feedback coupling 708 that can be used to convey feedback between the secondary and primary sides of the driver device, as well as the provision of a separate operating voltage VDD from the separation transformer 704 to those parts of the secondary side that need it. Additionally the driver device of fig. 7 comprises a control bus interface 709 that the second stage controller 707 may use to communicate over e.g. a DALI bus or some other control bus that links the driver device to a lighting control system.

**[0040]** A driver device of the kind shown in fig. 7 can be used to build a luminaire. The luminaire comprises a least one semiconductor light-emitting device in addition to the driver device of the kind described above.

**[0041]** A method for providing variable electric current to at least one semiconductor light-emitting device comprises forming control pulses of variable amplitude and duty cycle, and conducting said control pulses to a control input of a switch driver circuit. The switch driver circuit responds to voltages exceeding a first threshold at said control input by enabling the providing of switching pulses to the current switch of a switched-mode power supply. The switch driver circuit also responds to voltages between said first threshold and a second, further threshold at said control input by allowing an amplitude of a measured current to reach a value proportional to the voltage at said control input. The output current of said switched-mode power supply is used to provide said variable electric current.

**[0042]** Figs. 8 to 11 illustrate various alternative ways in which the duty cycle and amplitude of the control pulses may correspond to a desired average value of output current, which is essentially synonymous to a desired intensity of light emitted by the semiconductor light-emitting device. Each graph in figs. 8 to 11 may be considered as describing a train of control pulses during a period of time when the average value of output current is increased from a minimum value to a maximum value. Thus the horizontal axis in each graph in figs. 8 to 11 may be considered to represent time, and the vertical axis may be considered to represent the amplitude of the control pulses. Alternatively the horizontal axis in figs. 8 to 11 may be considered to represent desired average value of output current (i.e. desired intensity of light), so that the changes in duty cycle represented by the actual pulses in the graphs are to be taken schematically as representing the approximate value of duty cycle at various locations of the horizontal axis.

**[0043]** Control pulses of increasingly larger amplitude may be formed for providing the at least one semiconductor light-emitting device with increasing average electric current within a first range. Similarly control pulses of increasingly greater duty cycle may be formed for providing said at least one semiconductor light-emitting device with increasing average electric current within a second range. In the case of fig. 8 the first and second ranges overlap in full, so the development towards brighter intensity of light (i.e. advancing from left to right on the horizontal axis) involves gradually increasing both the duty cycle and the amplitude of the control pulses.

**[0044]** In fig. 9 said first range is a range from a maximum average current down to a knee point at the center of the graph, and the second range is a range from said knee point down to a minimum average current. In fig. 9 also the maximum duty cycle is 100%, which means that as an extreme value the control "pulses" are considered to follow each other without a break in between, practically resulting in a continuous control signal. Thus e.g. dimming the light from maximum intensity involves first decreasing the amplitude of the control "pulses", i.e. decreasing the value of the continuous control signal. If the dimming is continued beyond the knee point, the amplitude of the control pulses is not decreased any more. It stays constant, but the duty cycle of the control pulses is gradually decreased until maximal dimming is achieved with the minimum duty cycle.

**[0045]** In fig. 10 said second range is a range from a maximum average current down to a knee point, and said first range is a range from said knee point down to a minimum average current. In other words, e.g. dimming the light from maximum intensity involves first decreasing the duty cycle of the control pulses, keeping their amplitude constant. If the dimming is continued beyond the knee point, the duty cycle of the control pulses is not decreased any more. It stays constant, but the amplitude of the control pulses is gradually decreased until maximal dimming is achieved with the minimum control pulse amplitude. It is important to note that if the switch driver circuit operates like e.g. the MP24894, the amplitude of meaningful control pulses may not become smaller than the first threshold, because the switch driver circuit would interpret any EN/DIM voltage levels smaller than the first threshold as commands to disable the whole provision of switching pulses.

**[0046]** Fig. 11 illustrates a case in which the first and second ranges described above partially overlap. Dimming the light from maximum intensity involves first decreasing the amplitude of the control "pulses", i.e. decreasing the value of the continuous control signal, and beginning to decrease also the duty cycle after some desired lighting intensity that is higher than the knee point. If the dimming is continued beyond the knee point, the amplitude of the control pulses is not decreased any more. It stays constant, but the duty cycle of the control pulses is gradually decreased until maximum dimming is achieved with the minimum duty cycle. Similar partial overlapping can be applied also if the role of the first and second ranges are inversed, like in fig. 10, where the lowest intensities are achieved by changing the amplitude of the control pulses and the highest intensities involve changing their duty cycle.

**[0047]** Fig. 12 illustrates a driver device for providing variable electric current to at least one semiconductor light-emitting device. Blocks 702, 703, 704, 705, 708, and 709 serve similar purposes as the correspondingly numbered blocks in fig. 7, and their detailed description is thus omitted here. The driver device comprises a (second stage, or output stage) switched-mode power supply 1201 for generating an output current of the driver device. Said switched-mode power supply 1201 may have a general topology like that shown in more detail in fig. 13. It comprises a current switch 1301 and a switch driver circuit 1302 configured to provide switching pulses to the current switch 1301 at a switching frequency.

**[0048]** A processor 1202 is configured to provide a control signal in the form of a pulse train at a digital output, which is coupled to a control input 1303 of the switched-mode power supply 1201. On one hand, the control signal is taken to an enabling input pin EN of the switch driver circuit 1302, so that the pulses in the control signal cause repeatedly enabling and disabling the switch driver circuit 1302 at a frequency that can be called the PWM frequency and that is typically significantly smaller than the switching frequency. On the other hand, the control signal is filtered in an RC filter 1304, and the resulting filtered control signal is taken to a current feedback modifier circuit 1305, which has the role of changing the feedback gain of the current feedback circuit. In the implementation shown in fig. 13 the RC filter 1304 essentially transforms the original pulsed control signal into a control voltage, which is coupled to the base of a switching transistor in the current feedback modifier circuit 1305 with the effect of changing the effective resistance of the current sensing resistor arrangement. This in turn has the effect of changing the momentary maximum and/or minimum current that is allowed to flow through the semiconductor light-emitting device(s). Assuming that the amplitude of the pulses in the original control signal remains fixed, the control voltage brought to the current feedback modifier circuit 1305 reflects the duty cycle of the original control signal.

**[0049]** Figs. 12 and 13 thus illustrate a driver device in which the controlling processor 1202 may apply hybrid control, i.e. change both the amplitude and the duty cycle of the current through the LEDs, with only a single digital output of the processor being dedicated to this purpose. Compared to an approach like that of e.g. fig. 7 this involves the drawback that the analog and PWM control aspects are closely linked, because both may depend on the duty cycle of the control signal. However, the close linking may be loosened for example by using a filter with strongly frequency-dependent transfer function in place of the simple RC filter 1304, so that the gain of the current feedback modifier circuit 1305 would become primarily dependent on PWM frequency and not duty cycle. The PWM control of the switch driver circuit 1302 is not significantly dependent on the PWM frequency, as long as the PWM pulses brought to the EN input are long enough to keep the effect of possible soft-starting minimal. Soft-starting means that the switch driver circuit 1302 reacts to the leading edge of an ENABLE signal by beginning the production of switching pulses relatively slowly; if the PWM frequency becomes very high, the relative time spent in soft-starting may become significant at least at small duty cycles.

**[0050]** The exemplary embodiments described above do not constitute an exhaustive or limiting description of the scope of protection defined by the appended claims, but variations and modifications are possible. For example, filters introduced above for the purpose of converting a pulsed signal into a voltage level have been described as RC filters, but also other basic filter types can be used. For example the combination of an RC filter 601 and buffer amplifier 602 of fig. 6 may be replaced with an integrator type circuit. Also the buffer switch 604 shown in fig. 6 can be replaced with a serial switch that selectively cuts or connects the conductive connection between point 603 and the output. Dimming and brightening are notably reciprocal operations, so if something is said to take place during dimming, an inverse course of events typically takes place during brightening. Only single-channel driver devices have been described for clarity and simplicity, but the driver device may well have two or more second stage SMPS's coupled in parallel, each of them controlled in a similar way but independently of the other channels.

## Claims

1. A driver device for providing variable electric current to at least one semiconductor light-emitting device, comprising:

   - a switched-mode power supply for generating an output current of the driver device, the switched-mode power supply comprising a current switch,
   - a switch driver circuit configured to provide switching pulses to said current switch at a switching frequency,
   - a control input of said switch driver circuit, wherein said switch driver circuit is configured to respond to voltages exceeding a first threshold at said control input by enabling said providing of switching pulses and to voltages between said first threshold and a second, further threshold at said control input by allowing an amplitude of a measured current to reach a value proportional to the voltage at said control input, and
   - a control pulse formatter coupled to said control input and configured to provide said control input with control pulses of variable amplitude exceeding said first threshold at a pulse width modulation frequency smaller than said switching frequency.

2. A driver device according to claim 1, wherein said switch driver circuit is an integrated circuit, and said control input is an input pin of said integrated circuit.

3. A driver device according to claim 1 or 2, comprising a current sensing resistor on a current path through the switched-mode power supply, wherein said switch driver circuit is configured to respond to said voltages between said first and second thresholds at said control input by allowing a potential difference across said current sensing resistor to reach a value proportional to the voltage at said control input during each switching pulse.

4. A driver device according to any of the preceding claims, wherein:

   - said control pulse formatter comprises a first buffer for receiving a first pulse train and a second buffer for receiving a second pulse train,
   - said first buffer is configured to form a control voltage depending on a characteristic of said first pulse train, wherein said characteristic comprises at least one of: a frequency of said first pulse train, a duty cycle of said first pulse train,
   - said second buffer is configured to chop said control voltage depending on pulses of said second pulse train, and
   - chopped lengths of said control voltage constitute said control pulses.

5. A driver device according to claim 4, comprising a processor with a first output and a second output, wherein said processor is configured to provide said first pulse train at said first output and said second pulse train at said second output.

6. A driver device according to claim 4 or 5, wherein said first buffer comprises an RC filter followed by a buffer amplifier.

7. A driver device according to any of claims 4 to 6, wherein said second buffer comprises a buffer switch operated by pulses of said second pulse train and coupled to alternatively block or pass the control voltage depending on the state of conduction of the buffer switch.

8. A luminaire, comprising at least one semiconductor light-emitting device and a driver device according to any of claims 1 to 7.

9. A method for providing variable electric current to at least one semiconductor light-emitting device, comprising:

   - forming control pulses of variable amplitude and duty cycle,
   - conducting said control pulses to a control input of a switch driver circuit, wherein said switch driver circuit responds to voltages exceeding a first threshold at said control input by enabling the providing of switching pulses to the current switch of a switched-mode power supply, and to voltages between said first threshold and a second, further threshold at said control input by allowing an amplitude of a measured current to reach a value proportional to the voltage at said control input, and
   - using the output current of said switched-mode power supply to provide said variable electric current.

10. A method according to claim 9, wherein said forming of control pulses comprises:

    - forming control pulses of increasingly larger amplitude for providing said at least one semiconductor light-emitting device with increasing average electric current within a first range, and
    - forming control pulses of increasingly greater duty cycle for providing said at least one semiconductor light-emitting device with increasing average electric current within a second range.

11. A method according to claim 10, wherein said first range and said second range are at least partly over-

lapping.

**12.** A method according to claim 10, wherein said first range is a range from a maximum average current down to a knee point, and said second range is a range from said knee point down to a minimum average current.

**13.** A method according to claim 10, wherein said second range is a range from a maximum average current down to a knee point, and said first range is a range from said knee point down to a minimum average current.

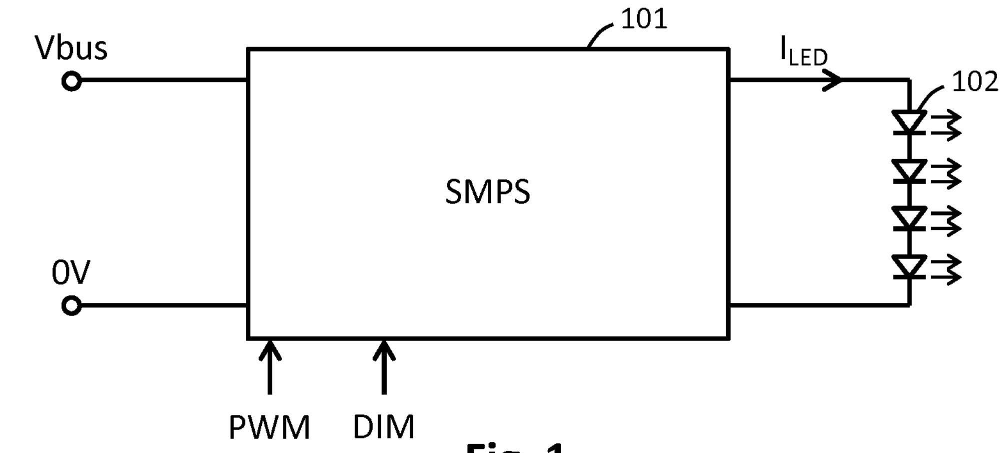



Fig. 1

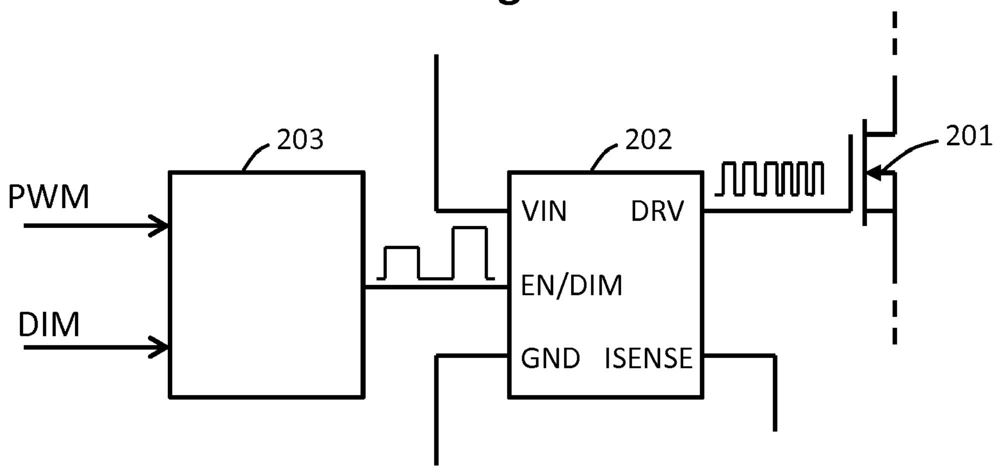



Fig. 2

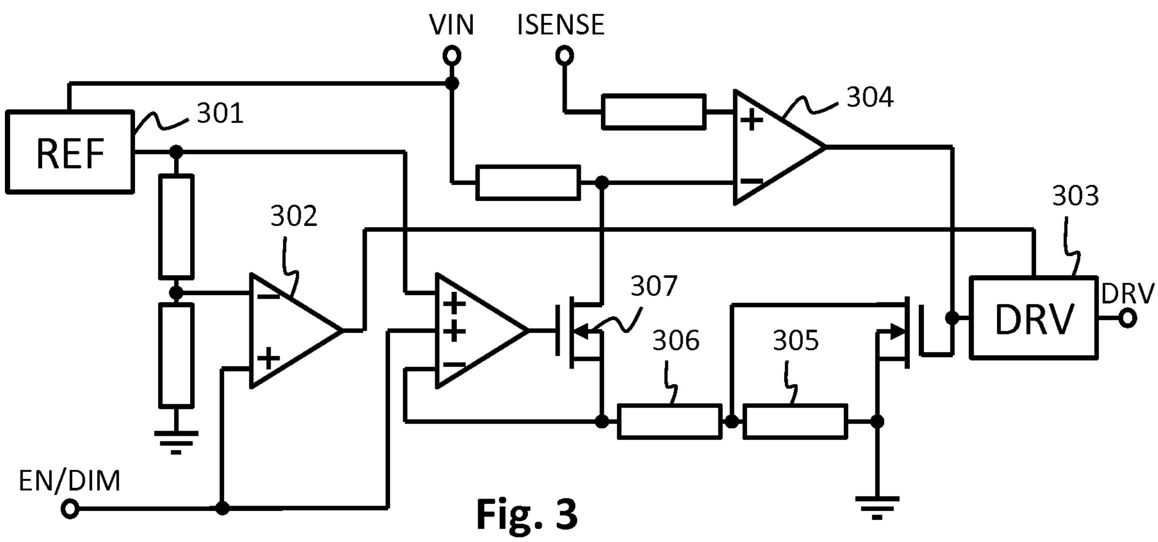
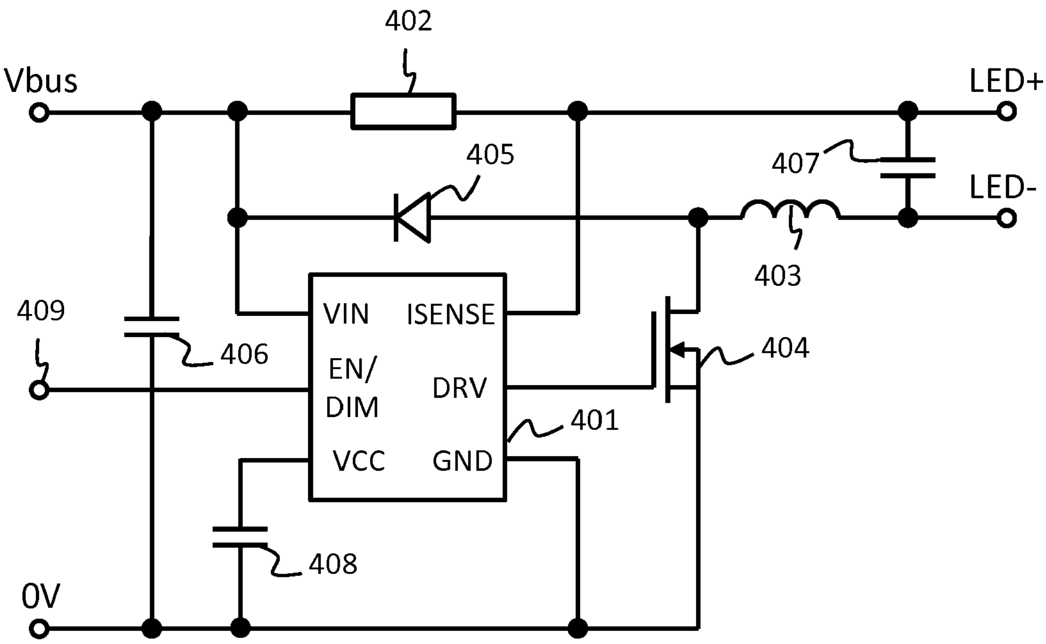



Fig. 3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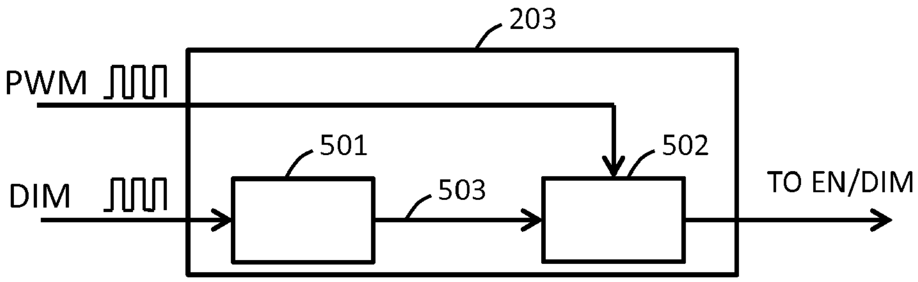
408
0V

Fig. 4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503
TO EN/DIM

Fig. 5

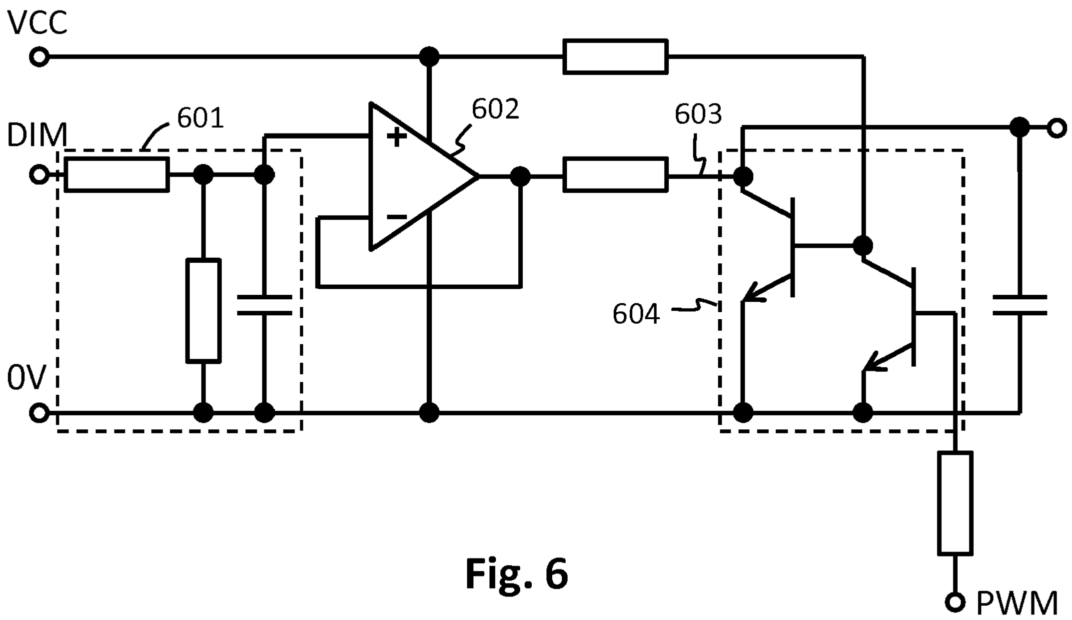
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Fig. 6

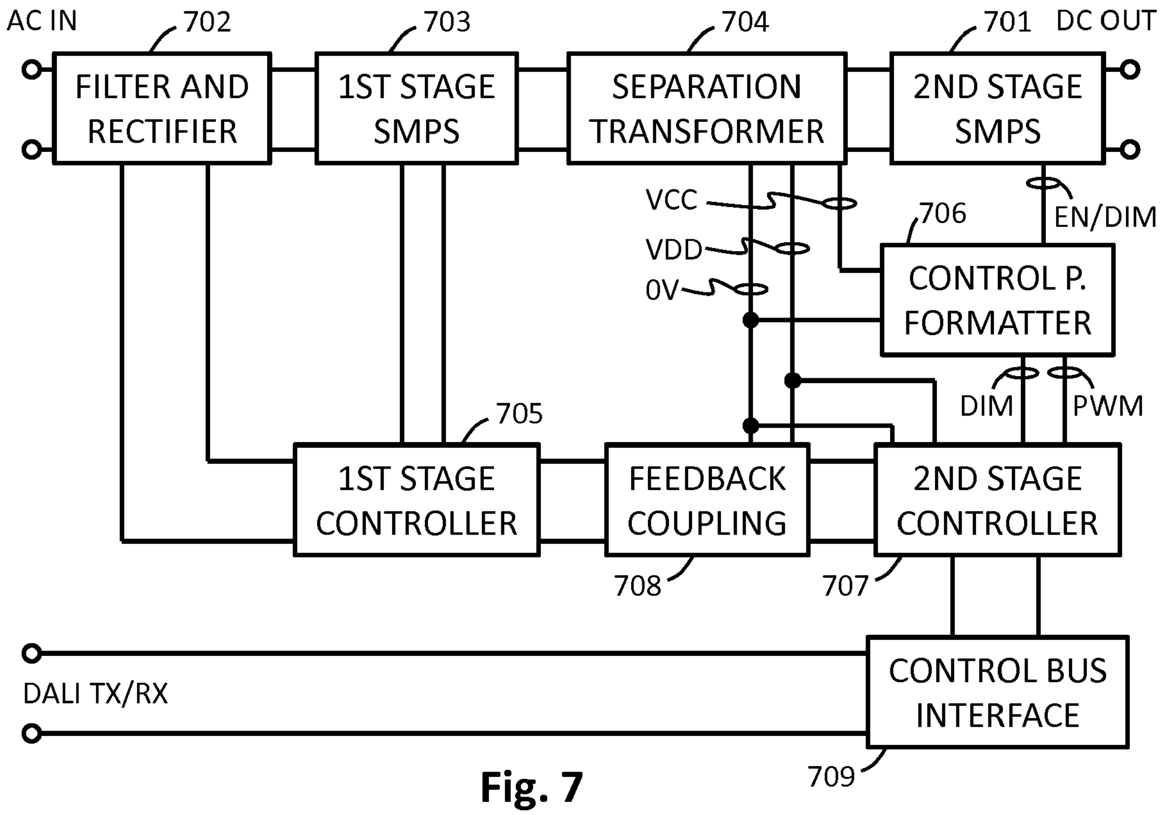
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Fig. 7

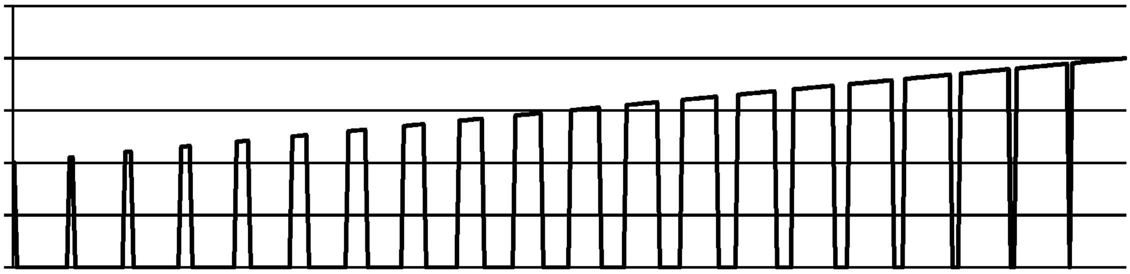


Fig. 8

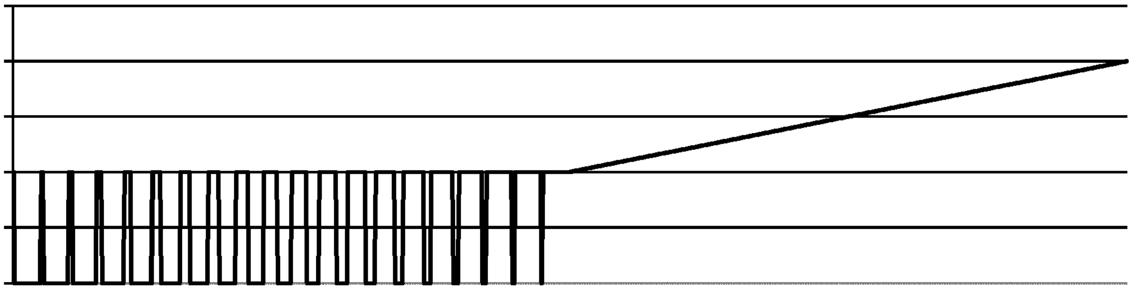


Fig. 9

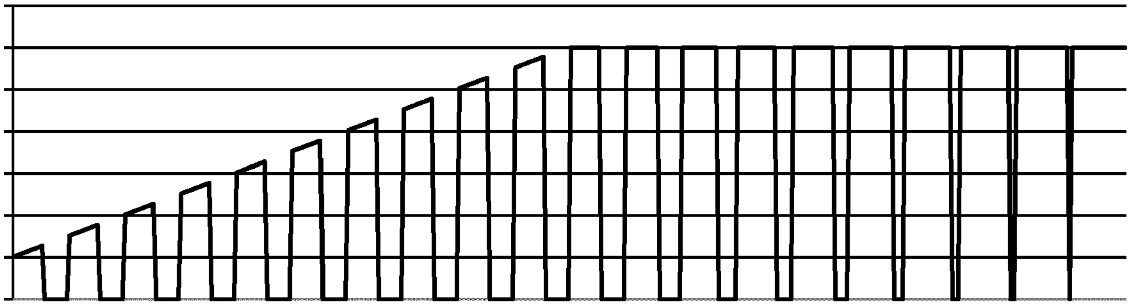


Fig. 10

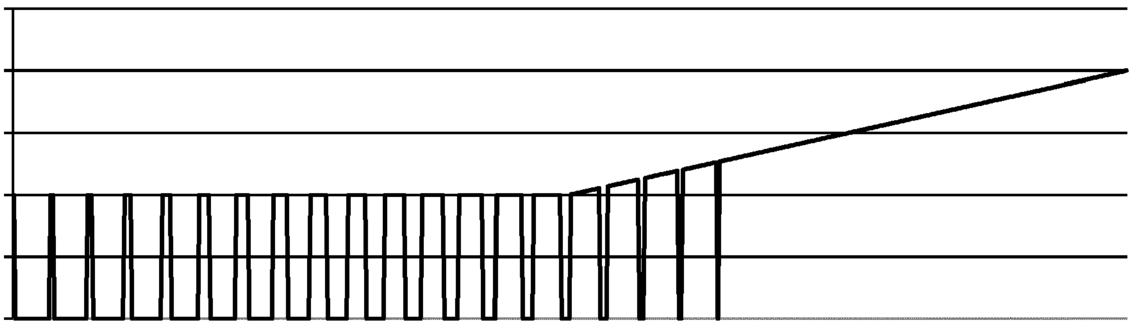
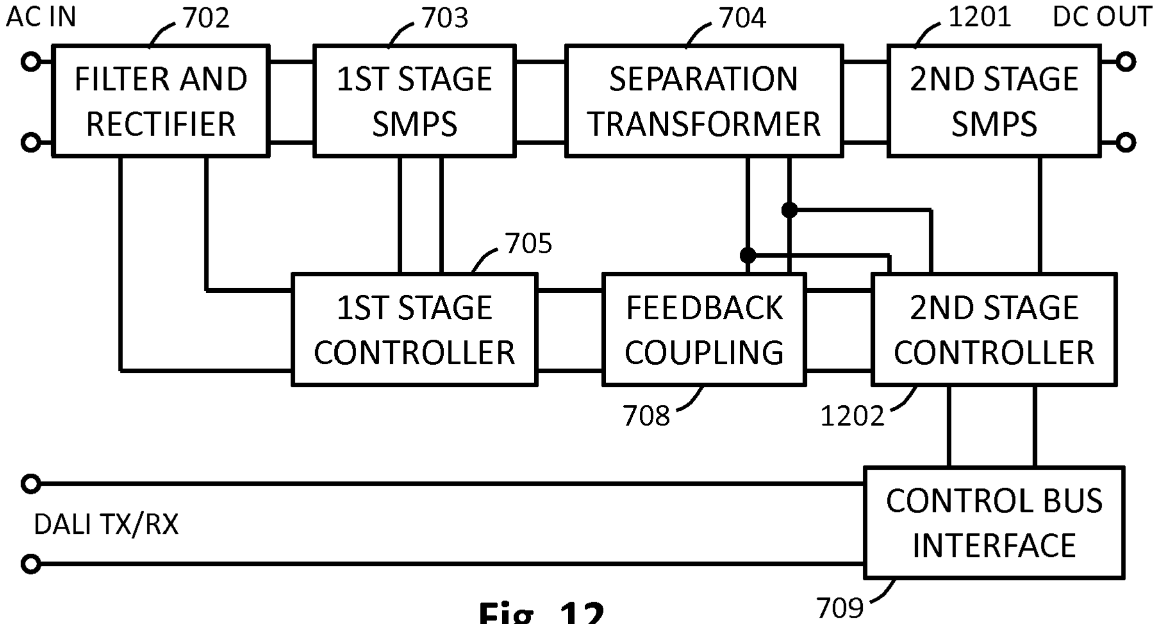


Fig. 11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CONTROL BUS INTERFACE
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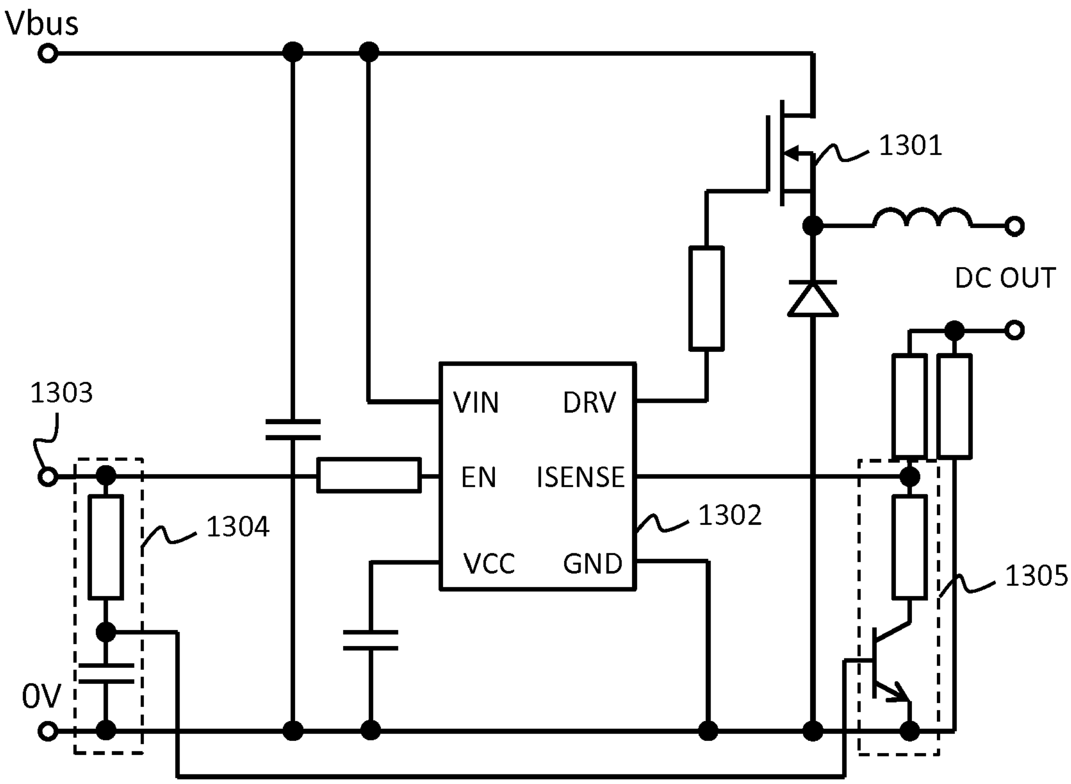
**Fig. 12**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1305
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**Fig. 13**

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# EUROPEAN SEARCH REPORT

Application Number
EP 15 15 0646

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H05B

The present search report has been drawn up for all claims

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| Place of search | Date of completion of the search | Examiner |
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| Munich | 27 July 2015 | Burchielli, M |

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27-07-2015

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