DEVICE AND METHOD FOR DRIVING LEDS

FIELD OF THE INVENTION

The present invention relates to a device and method for driving light emitting diodes (LEDs) using switched mode power supply configuration. The invention is particularly suited for the design of a LED current controller and will be described in this context.

BACKGROUND TO THE INVENTION

The following discussion of the background of the invention is intended to facilitate an understanding of the present invention. However, it should be appreciated that the discussion is not an acknowledgement or admission that any of the material referred to was published, known or part of the common general knowledge in any jurisdiction as at the priority date of the application.

Light Emitting Diodes (LEDs) are often driven by controller circuits to fulfill one or more objectives. As LEDs are sensitive to current and voltage fluctuations, one of the most important objectives for LED controller circuits is to provide appropriate current to drive the LEDs under supply voltage or load variations.

Pulse-Width Modulation (PWM) based controllers have been developed to provide appropriate current to LEDs under supply voltage/load variations. Most PWM controllers are switched-mode based controllers involving the use of electronic switches such as MOSFET as a means for regulating the current input to the LEDs.

Fig. 1 illustrates a typical buck-boost LED controller used for an isolated AC application. The current driver circuitry is based on an analog PWM controller, which includes the use of current feedback resistors **13**; opto-couplers **14**; and polarized capacitors **12**. The current driver circuitry further includes an analog PWM controller **15**.

The PWM based controller circuit has several disadvantages listed as follows:

- As the current-sense feedback resistors **13** are in the current path of the power MOSFET and the LEDs, it dissipates a lot of electrical energy. This is a loss of electrical energy as the feedback resistors **13** consume electrical energy (which is dissipated as heat) which is not producing useful work. Moreover, such feedback resistors **13** are typically power resistors which generate considerable heat and generally require thicker copper design when implemented on a printed circuit board (PCB). This increases the overall cost of implementation.

- The lifetime of the polarized capacitors **12** is typically much shorter than the lifetime of the LEDs. When one or more polarized capacitors **12** break down, they lead to short circuits which may further cause the malfunctioning of the driver circuitry. Such malfunctioning is likely to shorten the lifetime of the LEDs due to a cascading malfunctioning effect.

- The polarized capacitors **12** further introduce phase differences in the circuit which decreases power factor and the overall useful electrical power efficiency.

- The opto-couplers **14** are typically expensive electrical components which will increase the overall cost of implementing the LED controller.

In addition to the above disadvantages, the Applicant submits that generic PWM controllers (whether analogue or digital) work based on fixed/narrow frequencies range and does not ensure that the controller is working in a discontinuous mode when the operating frequency changes.

It is thus an object of the invention to overcome, or at least ameliorate in part, one or more of the aforementioned problems.

SUMMARY OF THE INVENTION

Throughout this document, unless otherwise indicated to the contrary, the phrase "comprising", "consisting of", and the like, are to be construed as inclusive and not exhaustive.

In accordance with a first aspect of the present invention there is a device for providing electrical current to at least one Light Emitting diode (LED) via a switch mode power converter comprising: at least one Integrated Circuit (IC), the IC programmable using a hardware description language; an electronic switch configurable to have a switching time period; an Analogue to Digital converter (ADC), the ADC configured to obtain a digitized voltage input; a voltage comparator, the voltage comparator configured to obtain a discharge time of an inductive element of the switch mode power converter at each time period; wherein in operation, the at least one IC is programmed to obtain the digitized voltage input, the discharge time of the inductive element, the desired electrical current, a reference constant value, and the switching time period of the electronic switch as inputs and therein calculate the switch-on time of the electronic switch at each switching time period, so that the switch-on time of the electronic switch regulates the electrical current flowing into the at least one LED.

Preferably, the at least one IC is an application-specific integrated circuit (ASIC).

Preferably, the switch-on time of the electronic switch is calculated according to the following formula:

$$T_{ON} = \frac{I_{OUT} * T}{K * V_{IN} * T_{OFF}}$$

Where T_{ON} is the switch-on time of the electronic switch, I_{OUT} is the desired electrical current; T is the switching time period of the electronic switch; K is the reference constant value; T_{OFF} is the discharge time of the inductive element of the switch mode power and V_{IN} is the digitalized voltage input.

Preferably, for an isolated alternating current (AC) fly back configuration having the inductive element as a transformer isolating the at least one LED at the secondary end of the transformer, the reference constant K is calculated according to the following formula:

$$K = \frac{1}{2 * \sqrt{L_1 * L_2}}$$

wherein L_1 is the inductance value of the primary winding of a transformer and L_2 is the inductance value of the secondary winding of the transformer. Preferably, the transformer is a planar transformer.

Alternatively, for a non-isolated direct current (DC) fly back configuration, the reference constant value K is calculated according to the following formula:

$$K=\frac{1}{L_3}$$

wherein L_3 is the inductance value of the inductive element in the fly back configuration.

Preferably, the value of T_{ON} is updated at each time period based on comparing an value A with a value B; the formulas of A and B are respectively:

$$A= V_{IN} * T_{ON} * T_{OFF}; \text{ and}$$

$$B= (1/K) * I_{OUT} * (T_{ON} + T_{OFF} + T_{CALC})$$

Wherein T_{CALC} is the time after the discharge time of the inductive element to compute the formula and the switching time period of the electronic switch is the summation of T_{ON}, T_{OFF} and T_{CALC};

such that when the value of A is greater than B, the value of T_{ON} is decreased by a predetermined number of clock cycles; when the value of A is smaller than B, the value of T_{ON} is increased by the predetermined number of clock cycles; and when the value of A is equals to B, no change is made to T_{ON}.

Preferably, the device configured for adjustment of the electrical current as a function of temperature by means of a thermistor positioned at the junction of each LED; the device further configured to update the electrical current output via updating the predetermined number of clock cycles.

Preferably, the electronic switch is a metal–oxide–semiconductor field-effect transistor (MOSFET), and in operation, the MOSFET is configured to work in a discontinuous mode.

Preferably, the ADC, voltage comparator and oscillator are integrated into the IC.

In accordance with a second aspect of the present invention there is a method for providing electrical current to at least one Light Emitting Diode (LED) via a switch mode power converter comprising the steps of:

(i) obtaining (a) a digitized voltage input; (b) a switching time period of an electronic switch; (c) a discharge time of an inductive element of the switch mode power converter; (d) the desired value of the electrical current; and (e) a digital reference as inputs and

(ii) calculating a switch-on time of the electronic switch at each switching time period;

(iii) regulating the electrical current flowing into the at least one LED at each switching time period based on the switch-on time of the electronic switch; and

(iv) repeating steps (i) to (iii) for each switching time period.

Preferably, the switch-on time of the electronic switch T_{ON} is calculated according to the following formula:

$$T_{ON} = \frac{I_{OUT} * T}{K * V_{IN} * T_{OFF}}$$

Wherein I_{OUT} is the desired electrical current; T is the switching time period of the electronic switch; K is a reference constant; T_{OFF} is the switch-off time of the electronic switch at each switching time period and V_{IN} is the digitized voltage input.

Preferably, for an isolated alternating current (AC) source input having a transformer isolating the at least one LED to the secondary end of the transformer, the constant gain value K is calculated according to the following formula:

$$K = \frac{1}{2 * \sqrt{L_1 * L_2}}$$

wherein L_1 is the inductance value of the primary winding of a transformer and L_2 is the inductance value of the secondary winding of the transformer.

Alternatively, for a non-isolated direct current (DC) fly-back configuration, the reference constant K is calculated according to the following formula:

$$K = \frac{1}{L_3}$$

wherein L_3 is the inductance value of an inductive element in the fly-back configuration.

Preferably, the value of T_{ON} is updated based on comparing a value A with a value B ; the formulas of A and B are respectively:

$A = V_{IN} * T_{ON} * T_{OFF}$; and

$B = (1/K) * I_{OUT} * (T_{ON} + T_{OFF} + T_{CALC})$

Wherein T_{CALC} is the time after the discharge time of the inductive element to compute the formula and the switching time period of the electronic switch is the summation of T_{ON}, T_{OFF} and T_{CALC};

such that when the value of A is greater than B, the value of T_{ON} is decreased by a predetermined number of clock cycles; when the value of A is smaller than B, the value of T_{ON} is increased by the predetermined number of clock cycles; and when the value of A is equals to B, no change is made to T_{ON}.

BRIEF DESCRIPTION OF THE DRAWINGS

The following invention will be described with reference to the following drawings of which:

Fig. 1 illustrates a prior art LED current controller circuit.

Fig. 2 illustrates a configuration of the LED driver circuit in accordance with the first embodiment of the invention for isolated alternating current (AC) application.

Fig. 3 illustrates a configuration of the LED driver circuit in accordance with the second embodiment of the invention for non-isolated direct current (DC) application.

Fig. 4 illustrates a flow chart for implementation of a digital algorithm in accordance with the first and second embodiment of the invention.

Fig. 5 illustrates possible waveforms at the gate and drain of the electronic switch (MOSFET) in accordance with the first and second embodiment embodiments of the invention.

Other arrangements of the invention are possible and, consequently, the accompanying drawings are not to be understood as superseding the generality of the preceding description of the invention.

DETAILED DESCRIPTION OF THE INVENTION

In context of the description, the term 'current' will generally be understood to mean 'electrical current' unless otherwise indicated.

In accordance with the first embodiment of the invention shown in Fig. 2 there is a device for providing electrical current to at least one Light Emitting diode **20**. The device is a LED driver **20** for an isolated alternating current (AC) application. The LED driver comprises transformer **23**, fly-back converter **22**, voltage divider **24**, Analog-to-digital converter (ADC) **26**, electronic switch **28**, voltage comparator **30**, bridge rectifier **32**, Integrated circuit (IC) **34** and an electronic oscillator **36**.

Transformer **23** is an isolation transformer. Transformer **23** decouples a LED load **100** from the rest of the circuitry. Each LED **100** is connected in series with other LEDs **100**. The winding ratio of transformer **23**is configured according to the number of LEDs in LED load **100**. . Transformer **23** may be a planar transformer or other low-loss transformers as known to a person skilled in the art.

Resistor $\mathbf{R_P}$ and capacitor $\mathbf{C_P}$ are connected in a parallel configuration with the primary end of the transformer **23**. A diode $\mathbf{D_P}$ is connected to the Resistors $\mathbf{R_P}$, capacitor $\mathbf{C_P}$, and the transformer **23**. The conducting end of the diode $\mathbf{D_P}$ is connected in a series configuration to the primary end of the transformer **23**. The non-conducting end of the diode $\mathbf{D_P}$ is connected in series configuration to the resistor $\mathbf{R_P}$ and capacitor $\mathbf{C_P}$.

A capacitor $\mathbf{C_S}$ is connected in parallel to the secondary end of the transformer **23**. A diode $\mathbf{D_S}$ is connected to the secondary end of the transformer **23** and the capacitor $\mathbf{C_S}$. The conducting end of the diode $\mathbf{D_S}$ is connected to the secondary end of the transformer **23** in a series configuration. The non-conducting end of the diode $\mathbf{D_S}$ is connected to the capacitor $\mathbf{C_S}$ in a series configuration. The LED load **100** is connected in a parallel configuration to the capacitor $\mathbf{C_S}$.

Voltage divider **24** comprises a series of standard resistors. For illustration, voltage divider **24** is represented using standard resistors $\mathbf{R_1}$, $\mathbf{R_2}$. For an AC supply voltage of 230 VAC, the resistance value for $\mathbf{R_1}$ is about 300kΩ and for $\mathbf{R_2}$ is about 2.2kΩ. During operation, the voltage between $\mathbf{R_1}$ and $\mathbf{R_2}$ is tapped by ADC **26**. The tapped voltage is converted to a digital value $\mathbf{V_{DD}}$. One end of $\mathbf{R_2}$ is connected to electrical ground.

The ADC **26** is suited to operate in the range of 50 to 120 Hz. In order for the embodiment to work, the minimum resolution of the ADC **26** should be 8-bit. The digitized voltage of the ADC **26** may also be used as an under-voltage security lock.

Electronic switch **28** is typically a power transistor. In this particular embodiment, electronic switch **28** is a MOSFET. The drain of the electronic switch **28** is connected to the conducting end of the diode $\mathbf{D_P}$. The gate of the electronic switch **28** is connected to the output pin of the IC **34**, and the source of the electronic switch **28** is connected to the electrical ground.

Voltage comparator **30** is connected to the primary end of the transformer **23** via a resistor $\mathbf{R_5}$. Resistor $\mathbf{R_5}$ is in turn connected in a series configuration with resistor $\mathbf{R_6}$. When in operation, voltage comparator **30** obtains the voltage between resistor $\mathbf{R_5}$ and

resistor $\mathbf{R_6}$. The obtained voltage is compared with a voltage reference $\mathbf{V_{REF}}$. $\mathbf{V_{REF}}$ is typically configured to be the same value as $\mathbf{V_{DD}}$. Voltage comparator **30** is typically (but not limited to), an operational-amplifier.

The bridge rectifier **32** is configured to provide a rectified output from the AC mains. The AC mains may be either 110 VAC or 230 VAC.

The IC **34** is typically an Application Specific Integrated Circuit (ASIC). In this regard, it is to be appreciated that ADC **26**, voltage comparator **30**, electronic oscillator **36** may be integrated with IC **34**. In addition, IC **34** may further comprise Regulators, Power-on-reset, MOSFET driver, , One-time programmable (OTP) memory, EEPROM, Flash and/or other programmable memory blocks as known to a person skilled in the art. IC **34** may be programmed using hardware description language (HDL) such as Verilog, VHDL, or other hardware description language as known to a person skilled in the art.

The IC **34** is programmed and configured to receive five inputs; i.e.

(a.) A reference constant **K**;

(b.) Desired reference current $\mathbf{I_{OUT}}$;

(c.) The digitized voltage value $\mathbf{V_{DD}}$ obtained from the ADC **26**;

(d.) A time value $\mathbf{T_{OFF}}$ of the discharge of the core of transformer **23** measured through voltage comparator **30**; and

(e.) A switching period **T** (i.e. the switching period of the electronic switch **28**) as illustrated in Fig. 5.

In relation to the switching period of the electronic switch **28**, the electronic oscillator **36** generates an operating frequency of 20 MHz, i.e. at a time period of 50 nano seconds. The switching time of the switch mode power supply (SMPS) is related to the on/off of the electronic switch **28**. In the context of this embodiment, the switching time of the SMPS ranges from 30 kHz to 300 kHz.

Using the received five inputs, the IC **34** computes an output T_{ON} to drive the gate of the electronic switch **28** in accordance with formula 1.

$$T_{ON} = \frac{I_{out} * T}{K * V_{in} * T_{off}} \quad (1)$$

Where T_{ON} is the switch-on time of the electronic switch **28**, I_{OUT} is the desired reference current; T is the switching time period of the electronic switch **28**; K is the reference constant; T_{OFF} is the discharge time of the transformer **23** and V_{IN} is the digitalized voltage input.

The reference constant **K** is calculated based on the inductance value of the primary and secondary windings of the transformer **23** as described in formula 2.

$$K = \frac{1}{2 * \sqrt{L_1 * L_2}} \quad (2)$$

where L_1 is the inductance value of the primary windings of the transformer **23** and L_2 is the inductance value of the secondary windings of the transformer **23**. The value of reference **K** is stored in a memory within the IC **34**, the memory may be one-time programmable (OTP), flash or EEPROM. Alternatively the reference **K** may be hardcoded in the formula, i.e. the value of reference **K** is stored inside the IC **34** as registers, in which case the **K** value may not be updated during operation.

The electronic oscillator **36** (20 MHz frequency, 50 ns period) is coupled with an internal 10 bit counter to count T_{ON} and T_{OFF}. The 10 bit counter translates to 1024 clock cycles before overflow). This means that with the 10 bit internal counter, the 1024 clock cycles may be counted within 50ns * 1024 = 51.2μs. Hence, the counter is capable for counting between 19.53125 kHz up to 20 MHz. It is to be appreciated that the switching time **T** of the electronic switch **28** of 30 kHz to 300 kHz falls within the above range.The digital reference current I_{OUT} fixes the desired output current to drive the LEDs. The value of digital reference current I_{OUT} may be either stored in the memory of IC **34** or hardcoded in the formula, in which case the digital reference value I_{OUT} may not be updated during operation.

The embodiment will next be described in the context of its operation. As an illustration (and not meant to be exclusive), a voltage input of 230VAC is entered to drive the LED driver **20**. Eighteen LEDs **100** are connected in series with each other. The eighteen LEDs **100** form the LED load.

Fig. 5 illustrates typical voltage-time waveforms at the gate and drain of the electronic switch **28** when the LED driver **20** is in operation. A voltage overshoot at the drain of electronic switch **28** is measured. The voltage overshoot is proportional to the voltage across the LEDs **100**. The voltage overshoot value is used to measure the time of core discharge $\mathbf{T_{OFF}}$ using the voltage comparator **30** and a digital counter. The value of $\mathbf{T_{OFF}}$ is measured based on the time of the core discharge of the primary end of the transformer **23**.

During operation, V_{REF} is configured to be the same voltage reference of the input voltage V_{DD} as sampled by the ADC **26**. Such a configuration ensures that the electronic switch **28** is consistently working in discontinuous mode.

The value of T_{ON} is fine-tuned iteratively in accordance to the flow chart illustrated in Fig. 4 such that over a period (of clock cycles), the electrical current flowing into the LED load **100** is regulated by adjusting T_{ON}. The steps are described in the flow chart are described as follows:

The electronic switch **28** is activated for T_{ON} time. (Step **60**)

The T_{OFF} timing is computed based on the voltage comparator **30** and digital counter (Step **62**)

A value V_{IN} (V_{IN}=V_{DD}) is obtained from the ADC **26** (digitized value) (Step **64**)

Formula (3) is computed as follows: (Step **66**)

$$A = V_{IN} * T_{ON} * T_{OFF} \quad (3)$$

Formula (4) is computed as follows: (Step **68**)

$$B = (1/K) * I_{OUT} * (T_{ON} + T_{OFF} + T_{CALC}) \quad (4)$$

wherein T_{CALC} is the time after the discharge to compute the formula.

such that the switching period **T** of the electronic switch **28** is the summation of T_{ON}, T_{OFF} and T_{CALC}.

The actual implementation takes approximately 128 clock cycles.

The value of A and B are compared (Step **70**).

If A is greater than B, i.e. $A > B$, then T_{ON} is adjusted to $T_{ON} - N$ for the next time period T (Step **72**).

If A is smaller than B, i.e. $A < B$, then T_{ON} is adjusted to $T_{ON} + N$ (Step **74**).

In the situation where A is equals to B, there is no updating of T_{ON} and T_{ON} remains unchanged (Step **76**).

The value N is an adjustment value. N is the increment or decrement of the switch-on time T_{ON} of the MOSFET. The adjustment value N forms part of the feedback loop for stabilizing current I_{OUT} under supply variation. The value of N typically ranges between 1 and 128 number of clock cycles.

It is to be appreciated that for different differences of A and B, different values of N are used.

It is to be further appreciated that A and B is computed separately due to the complexity of performing hard-coded division, which is time-consuming and inefficient for this application. To overcome the problem, algebraic manipulation is used to compute the formulas (3) and (4) and therein compare the results between A and B.

The process Step **60** to **76** repeats itself until the circuit is switched off or according to other terminating condition as known to a person skilled in the art.

The T_{OFF} value may further be configured for short circuit protection of the LED load **100**. For the purpose of short circuit protection, the T_{OFF} value is compared with a

short circuit reference value $T_{OFF, SC}$. If a short circuit is present on the secondary winding of the transformer **23**, where the LED load **100** is, the T_{OFF} value will be shorter than the short circuit reference value $T_{OFF, SC}$, thereby activating the short circuit protection.

The Applicant has discovered that the use of the ASIC and the implementation of formula (1) to (4) are independent from the number of LEDs in the load. The implementation of the ASIC further omit the need for polarized capacitors on the main power supply, polarized capacitors with larger capacitance on the secondary windings of transformer **23**, feedback power resistors on the MOSFET and on the LED chain/load. The total efficiency (as well as power factor correction) of the system will thus increase as majority of the electrical power will be transferred to the LEDs instead of to the feedback resistors and capacitors. In addition, the cost of implementing the circuitry is typically lower than the prior art circuitry as described in Fig. 1, as the components used generally lower in cost as compared to specific components such as opto-couplers **14** (thereby omitting the need for voltage feedback on the secondary end of transformer **23**) and polarized capacitors.

In the above example, with eighteen LEDs (each LED **100** having a forward voltage of 3.2V) and an input of 230 VAC and a reference output current I_{OUT} of 350 milli-amperes (mA), an efficiency of as high as 94% is achieved. This is based on obtained demo-board simulation results, where the system power consumption is 21.5W. The total LED power consumption is 20.16 W such that the efficiency is 20.16 divided by 21.5, i.e. 93.8 %.

In addition, for the purpose of short circuit protection, if one LED **100** is shorted the formulas (1) to (4) are capable of adapting the value of T_{ON} to provide the right current to the working LEDs via the feedback mechanism described in Step **60** to **76**. The driver **20** is thus independent from the number of LEDs present on the secondary end of the transformer **23** (i.e. the load side).

An additional security option is done computing the T_{ON} multiplied by the V_{IN} value. In order not to saturate the transformer core L_1, L_2 this value must be under a digital

threshold value $T_{ON,MAX}$. The digital threshold value $T_{ON,MAX}$ is calculated as Formula (5), assuming that the core saturates at 0.3 Tesla:

$$T_{ON,MAX} = (N_P * 0.3 * A_E) / (V_{IN}) \quad (5)$$

Where N_P is the number of primary windings, A_E is the effective area of the transformer, V_{IN} is the input voltage.

In accordance to the second embodiment of the invention as shown in Fig. 3 there is a device for providing electrical current to at least one Light Emitting diode **120**. The device is an LED driver **120** for a non-isolated DC application. The LED driver comprises fly-back converter **122**, voltage divider **124**, Analog-to-digital converter (ADC) **126**, electronic switch **128**, voltage comparator **130**, DC power supply **132** and an Integrated circuit chip (IC) **134** and electronic oscillator **136**.

Fly-back converter **122** comprises a diode **121** connected in a series configuration with inductor **123** and capacitor **125**. Inductor **123** and capacitor **125** are configured to be in a parallel configuration with the LED load **200**. Each LED **200** is connected in series to other LEDs **200**. The conducting end of the diode **121** is connected to the inductor **123**. The non-conducting end of the diode **121** is connected to the capacitor **125**.

Voltage divider **124** comprises a series of standard resistors. For illustration, voltage divider **124** is represented using standard resistors $\mathbf{R_3}$, $\mathbf{R_4}$. The voltage between $\mathbf{R_3}$ and $\mathbf{R_4}$ is tapped by ADC **126** during operation. At a DC voltage of 12V, the value of $\mathbf{R_3}$ and $\mathbf{R_4}$ are about 47kΩ and 4.7kΩ respectively. One end of $\mathbf{R_4}$ is connected to electrical ground.

The ADC **126** operates in the range of 50 to 120 Hz. In order for the embodiment to work, the minimum resolution of the ADC **126** is 8-bit. The digitized voltage of the ADC **126** may be used as an under-voltage security lock. The tapped voltage between $\mathbf{R_3}$ and $\mathbf{R_4}$ is converted to a digital value $\mathbf{V_{DD}}$.

Electronic switch **128** is typically a power transistor. In this particular embodiment, electronic switch **128** is a MOSFET. The drain of the electronic switch **128** is

connected to the conducting end of the diode **121** and the inductor **123**. The gate of the electronic switch **128** is connected to the output pin of the IC **134**, and the source of the electronic switch **128** is connected to the electrical ground.

Voltage comparator **130** compares the voltage obtained at the drain of the electronic switch **128** with a voltage reference V_{REF}. Voltage comparator **130** is typically (but not limited to), an operational-amplifier.

The DC power supply **132** is configured to provide a DC output to the circuit. The DC output may range from 3V to 400V.

The IC **134** is typically an Application Specific Integrated Circuit (ASIC). In this regard, it is to be appreciated that ADC **126**, voltage comparator **130**, electronic oscillator **136** may be integrated with IC **134**. In addition, IC **134** may further comprise regulators, Power-on-reset, MOSFET driver, OTP memory, EEPROM, Flash and/or other programmable memory blocks as known to a person skilled in the art. IC **134** may be programmed using hardware description language (HDL) such as Verilog, VHDL, or other hardware description language as known to a person skilled in the art.

The IC **134** is programmed and configured to receive five inputs; i.e.

(a.) A reference constant **K**;

(b.) Desired reference current $\mathbf{I_{OUT}}$;

(c.) The digitized voltage value $\mathbf{V_{DD}}$ obtained from the ADC **126**;

(d.) A time value $\mathbf{T_{OFF}}$ of the core discharge of the inductor **123**; and

(e.) A switching period **T**, the switching period of the electronic switch **28** obtained from electronic oscillator **136**.

The electronic oscillator **136** generates an operating frequency of 20 MHz, i.e. a time period of 50 nano seconds. The switching time of the switch mode power supply

(SMPS) is related to the on/off of the electronic switch **128**. In the context of this embodiment, the switching time of the SMPS ranges from 30 kHz to 300 kHz.

Using the received five inputs, the IC **134** computes an output $\mathbf{T_{ON}}$ to drive the gate of the electronic switch **128** in accordance with formula 1.

The reference constant **K** is calculated based on the discharge time of the inductor **123** as described in formula 6.

$$K=\frac{1}{L_3} \tag{6}$$

where L_3 is the inductance value of the inductor **123**. The reference **K** is a digital value and could be stored in a memory within the IC **134**, the memory could be OTP, flash or EEPROM. or hardcoded in the formula, in which case the digital value is stored inside the ASIC **134** as registers; thus the digital value may not be changed during operation.

The electronic oscillator **136** (20 MHz frequency, 50 ns period) is coupled with an internal 10 bit counter to count T_{ON} and T_{OFF}. The 10 bit counter translates to 1024 clock cycles before overflow). This means that with the 10 bit internal counter, the 1024 clock cycle may be counted within 50ns * 1024 = 51.2μs. Technically speaking, the counter is capable for counting between 19.53125 kHz up to 20 MHz. Thus the switching time **T** of the electronic switch **128** of 30 kHz to 300 kHz falls within the above range.

The embodiment will next be described in the context of its operation.

Fig. 5 illustrates typical voltage-time waveforms at the gate and drain of the electronic switch **128** when the LED driver **120** is in operation. A voltage overshoot at the drain of electronic switch **128** is measured. The voltage overshoot value is used to measure the time of core discharge $\mathbf{T_{OFF}}$ using the voltage comparator **130** and a digital counter. The value of $\mathbf{T_{OFF}}$ is measured based on the discharge time of the inductor **123**. This is easily obtained via various methods as known to a person skilled in the art.

During operation, V_{REF} is configured to be the same voltage reference of the input voltage V_{DD} as sampled by the ADC **126**. This configuration ensures that the electronic switch **128** is consistently working in discontinuous mode.

The value of T_{ON} is fine tuned iteratively in accordance with the flow chart as illustrated earlier in Fig. 4. The process Step **60** to **76** repeats itself until the circuit is switched off or according to other terminating condition as known to a person skilled in the art.

The T_{OFF} value may further be configured for short circuit protection of the LEDs **200**. In this regard, the T_{OFF} value is compared with a short circuit reference value $T_{OFF,SC}$. If a short circuit is present on the secondary winding of the transformer **23**, where the LEDs **200** are, the T_{OFF} value will be shorter than the short circuit reference value, thereby activating the short circuit protection.

The digital reference I_{OUT} fixes the desired output current to drive the LEDs. The value of digital reference I_{OUT} is stored in the memory of IC **134** or hardcoded in the formula.

During operation, the value of T_{ON} is fine-tuned iteratively in accordance to the flow chart illustrated in Fig. 4 such that over a period (of clock cycles), the electrical current flowing into the LED load **100** is regulated by adjusting T_{ON}. The steps **60** to **74** are described as mentioned earlier. Steps **60** to **74** repeats itself until the circuit is switched off or according to other terminating condition as known to a person skilled in the art.

The T_{OFF} value may further be configured for short circuit protection of the LED load **200**. For the purpose of short circuit protection, the T_{OFF} value is compared with a short circuit reference value $T_{OFF,\,SC}$. If a short circuit is present on the inductor **123**, where the LED load **200** is, the T_{OFF} value will be shorter than the short circuit reference value $T_{OFF,\,SC}$, thereby activating the short circuit protection.

The digital reference I_{OUT} fixes the desired output current to drive the LEDs. The value of digital reference I_{OUT} may be either stored in the memory of IC **134** or

hardcoded in the formula, in which case the digital reference value I_{OUT} may not be updated during operation.

In addition, for the purpose of short circuit protection, if one LED **200** is shorted the formulas (1), (3), (4), (6) are capable of adapting the value of T_{ON} to provide the right current to the working LEDs via the feedback mechanism described in Step **60** to **76**. The driver **120** is thus independent from the number of LEDs **200** present.

An additional security option is done computing the T_{ON} multiplied by the V_{IN} value. In order not to saturate the inductor **123** this value must be under a digital threshold value $T_{ON,MAX}$. The digital threshold value $T_{ON,MAX}$ is calculated as illustrated in Formula (5), assuming that the core saturates at 0.3 Tesla:

With respect to both the embodiments, the Applicant observes that as the current is adjusted iteratively and based on the implementation of the ASIC programming, it is easy to dim the LED loads **100**, **200** using the present circuitry without additional components. Thus, it is to be appreciated that dimming may be achieved via adjusting the current reference value I_{OUT}.

It is to be further appreciated that if a user wishes to switch off the device under both the embodiments as described, he may simply do so by inputting the current reference value I_{OUT} to 0. The same user may switch on the device if he put a different value other than 0 in the I_{OUT} register.

Further, the drivers **20**, **120** may be configured for direct monitoring and adjustment of current as a function of temperature. In this regard, a thermistor may be positioned at the junction of each LED so that the controller may be adapted to auto update a different current output (via updating the value of N) for the LED loads **100**, **200** based on the junction temperature sensed. This ensures that the LEDs **100**, **200** are not over heated. Such a strategy will lengthen the life span of the LEDs **100**, **200**.

The above feature may be easily implemented via an additional enable pin on the ASIC **34**, **134** as known to a person skilled in the art.

By way of an example of the thermistor-based monitoring, if there are five white LEDs and one red LED connected in a series configuration, the thermistor may be positioned adjacent to the red LED (due to the fact that the red LED has the lower critical temperature as compared to white LEDs). Care should however be taken such that the red LED is positioned at a location where heat dissipation could take place readily. In this way, as soon as the critical temperature of the red LED is reached, the IC (ASIC) **34**, **134** decrease the current to the LED load.

For illustration, when the junction temperature of the red LED reaches 60 degree Celsius, the IC **34**, **134** will adjust the current to decrease by 10% (e.g. 300 mA). When the junction temperature of the red LED reaches 65 degree celsius, the IC **34**, **134** will adjust the current to decrease by 30% (250 mA); and when the junction temperature of the red LED is decreased to 55 degree Celsius, the IC **34**, **134** will resume the current to full load (350 mA).

It should be appreciated by the person skilled in the art that the invention is not limited to the examples described. In particular, the following additions and/or modifications can be made without departing from the scope of the invention:

- Field-programmable gate array (FPGA) can be used as an alternative to ASIC as known to a person skilled in the art.

- While the existing embodiments illustrate the LEDs loads **100**, **200** in the series configuration, the LEDs loads **100**, **200** may be arranged in a parallel configuration as known to a person skilled in the art, such that the driven current I_{OUT} is the average of the current in each single parallel chain.

- The IC **34**, **134** may be further configured to have more inputs for other purposes; and not be limited to five inputs.

- The adjustment value N as mentioned in step **74** is the increment or decrement of the switch on time T_{ON} of the MOSFET and may forms part of the stabilization filter loop. Typically the bigger the difference between A and B the bigger the value of N applied. As an example of a range, a ratio of 20 to 1 in terms of clock cycle is applied for AC/DC and from 5 to 1 in DC/DC.

- A 'Wake-up function' may be incorporated into the LED drivers 20, 200 via using motion sensor with digital interface or analog threshold.

- Although the LED drivers **20**, **200** as presented in the first and second embodiments described the invention being applied to a fly-back converter configuration, it is to be appreciated that the IC **34**, **134** and the formulas (1) to (6) are applicable to general switch mode power supplies including buck-boost converters, buck converters and boost converters (both isolated AC and non-isolated DC configurations).

- The formulas (1) to (6) is not limited to the frequency generated by the electronic oscillator **36**. In general, the higher the frequency generated, the bigger the design required for implementation; conversely the lower the frequency, the less precision on the current control. In this regard, 20MHz is a good compromise between precision and implementation.

It should be further appreciated by the person skilled in the art that features and modifications discussed above, not being alternatives or substitutes, can be combined to form yet other embodiments that fall within the scope of the invention described.

CLAIMS

1. A device for providing electrical current to at least one Light Emitting diode (LED) via a switch mode power converter comprising:

at least one Integrated Circuit (IC), the IC programmable using a hardware description language;

an electronic switch configurable to have a switching time period;

an Analogue to Digital converter (ADC), the ADC configured to obtain a digitized voltage input;

a voltage comparator, the voltage comparator configured to obtain a discharge time of an inductive element of the switch mode power converter at each time period;

wherein in operation, the at least one IC is programmed to obtain the digitized voltage input, the discharge time of the inductive element, the desired electrical current, a reference constant, and the switching time period of the electronic switch as inputs and thereafter calculate a switch-on time of the electronic switch at each switching time period, so that the switch-on time of the electronic switch regulates the electrical current flowing into the at least one LED.

2. A device according to claim 1, wherein the at least one IC is an application-specific integrated circuit (ASIC).

3. A device according to claim 2, wherein the switch-on time of the electronic switch is calculated according to the following formula:

$$T_{ON} = \frac{I_{OUT} * T}{K * V_{IN} * T_{OFF}}$$

where T_{ON} is the switch-on time of the electronic switch, I_{OUT} is the desired electrical current; T is the switching time period of the electronic switch; K is the reference constant ; T_{OFF} is the discharge time of the inductive element of the switch mode power converter and V_{IN} is the digitalized voltage input.

4. A device according to claim 3, wherein for an isolated alternating current (AC) fly back configuration having the inductive element as a transformer isolating the at least one LED at the secondary end of the transformer, the reference constant K is calculated according to the following formula:

$$K = \frac{1}{2 * \sqrt{L_1 * L_2}}$$

wherein L_1 is the inductance value of the primary winding of a transformer and L_2 is the inductance value of the secondary winding of the transformer.

5. A device according to claim 4, wherein the transformer is a planar transformer.

6. A device according to claim 3, wherein for a non-isolated direct current (DC) fly back configuration , the reference constant K is calculated according to the following formula:

$$K = \frac{1}{L_3}$$

wherein L_3 is the inductance value of the inductive element in the fly back configuration.

7. A device according to any one of claim 3 to 6, wherein the value of T_{ON} is updated at each time period based on comparing an value A with a value B ; the formulas of A and B are respectively:

$A = V_{IN} * T_{ON} * T_{OFF}$; and

$B = (1/K) * I_{OUT} * (T_{ON} + T_{OFF} + T_{CALC})$

wherein T_{CALC} is the time after the discharge time of the inductive element to compute the formula and the switching time period of the electronic switch is the summation of T_{ON}, T_{OFF} and T_{CALC};

such that when the value of A is greater than B, the value of T_{ON} is decreased by a predetermined number of clock cycles; when the value of A is smaller than B, the

value of T_{ON} is increased by the predetermined number of clock cycles; and when the value of A is equals to B, no change is made to T_{ON}.

8. A device according to claim 7, the device configured for adjustment of the electrical current as a function of temperature by means of a thermistor positioned at the junction of each LED; the device further configured to update the electrical current output via updating the predetermined number of clock cycles.

9. A device according to any one of the preceding claims, wherein the electronic switch is a metal–oxide–semiconductor field-effect transistor (MOSFET), and in operation, the MOSFET is configured to work in a discontinuous mode.

10. A device according to any one of the preceding claims, wherein the ADC, voltage comparator and oscillator are integrated into the IC.

11. A device according to any one of the preceding claims, wherein the minimum resolution of the ADC is 8-bit.

12. A device according to claim 4 or 6, wherein the T_{OFF} value is configured to be compared with a short circuit reference value such that in use, the T_{OFF} value is less than the short circuit reference value when a short circuit is present.

13. A method for providing electrical current to at least one Light Emitting Diode (LED) via a switch mode power converter comprising the steps of:

(i) obtaining (a) a digitized voltage input; (b) a switching time period of an electronic switch; (c) a discharge time of an inductive element of the switch mode power converter; (d) the desired value of the electrical current; and (e) a digital reference as inputs;

(ii) calculating a switch-on time of the electronic switch at each switching time period; and

(iii) regulating the electrical current flowing into the at least one LED at each switching time period based on the switch-on time of the electronic switch; and(iv) repeating steps (i) to (iii) for each switching time period.

14. A method according to claim 13, wherein the switch-on time of the electronic switch T_{ON} is calculated according to the following formula:

$$T_{ON} = \frac{I_{OUT} * T}{K * V_{IN} * T_{OFF}}$$

wherein I_{OUT} is the desired electrical current; T is the switching time period of the electronic switch; K is a reference constant; T_{OFF} is the switch-off time of the electronic switch at each switching time period and V_{IN} is the digitized voltage input.

15. A method according to claim 14, wherein for an isolated alternating current (AC) source input having a transformer isolating the at least one LED to the secondary end of the transformer, the reference constant K is calculated according to the following formula:

$$K = \frac{1}{2 * \sqrt{L_1 * L_2}}$$

wherein L_1 is the inductance value of the primary winding of the transformer and L_2 is the inductance value of the secondary winding of the transformer.

16. A method according to claim 14, wherein for a non-isolated direct current (DC) fly-back configuration, the reference constant K is calculated according to the following formula:

$$K = \frac{1}{L_3}$$

wherein L_3 is the inductance value of an inductive element in the fly-back configuration.

17. A method according to any one of claims 14 to 16, wherein the value of T_{ON} is updated at each switching period based on comparing a value A with a value B ; the formulas of A and B are respectively:

A= V_{IN} *T_{ON}*T_{OFF}; and

$$B= (1/K)*I_{OUT}*(T_{ON} + T_{OFF} + T_{CALC})$$

wherein T_{CALC} is the time after the discharge time of the inductive element to compute the formula and the switching time period of the electronic switch is the summation of T_{ON}, T_{OFF} and T_{CALC};

such that when the value of A is greater than B, the value of T_{ON} is decreased by a predetermined number of clock cycles; when the value of A is smaller than B, the value of T_{ON} is increased by the predetermined number of clock cycles; and when the value of A is equals to B, no change is made to T_{ON}.

18. A method according to any one of claims 13 to 17, wherein the minimum resolution of the digitized voltage input is 8-bit.

19. A method according to any one of claims 14 to 16, wherein the T_{OFF} value is compared with a short circuit reference value and where T_{OFF} is less than the short circuit reference value indicates that a short circuit is present.