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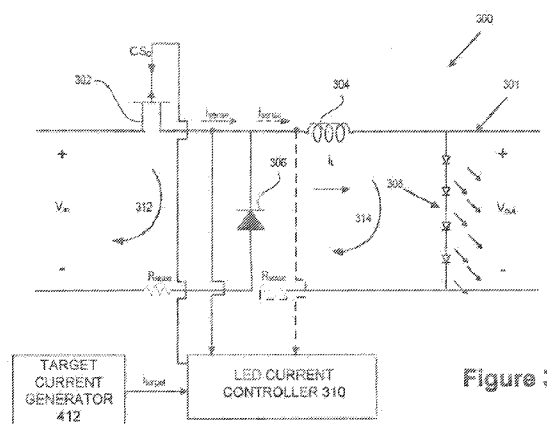
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(54) Title: ADJUSTABLE CONSTANT CURRENT SOURCE WITH CONTINUOUS CONDUCTION MODE ("CCM") AND DISCONTINUOUS CONDUCTION MODE ("DCM") OPERATION



(57) Abstract: A converter system and method of operating a converter system are disclosed. The converter system comprises a converter power stage that can operate in a Discontinuous Conduction Mode (DCM) in a range of output currents and a Continuous Conduction Mode (CCM) in another range of output currents. The converter power stage includes at least an inductor with an inductor value and a control switch. The converter power stage provides an average current. A current controller is coupled to the converter power stage. When the converter power stage operates in DCM, the current controller is configured to measure the inductor value of the inductor. Furthermore, the current controller can also be configured to measure an input-to-output conversion ratio from the converter power stage.

**ADJUSTABLE CONSTANT CURRENT SOURCE WITH CONTINUOUS
CONDUCTION MODE ("CCM") AND DISCONTINUOUS CONDUCTION
MODE ("DCM") OPERATION**

John L. Melanson

Cross-reference to Related Application

(1) This application is related to and cross-references U.S. Application Serial Number 12/107,613 entitled "Power Factor Correction (PFC) Controller and Method Using a Finite State Machine to Adjust the Duty Cycle of a PWM Control Signal" filed on April 22, 2008 (Inventor: John Melanson; Cirrus Docket No. 1684-IPD); U.S. Application Serial Number 12/110,714 filed on April 28, 2008 entitled "Discontinuous Conduction Mode (DCM) Using Sensed Current for a Switch-Mode Converter" (Inventor: John Melanson; Cirrus Docket No. 1679-IPD); and U.S. Application Serial Number 12/113,536 filed on May 1, 2008 entitled "Switch-Mode Converter Operating in a Hybrid Discontinuous Conduction Mode (DCM)/Continuous Conduction Mode (CCM) That Uses Double or More Pulses in a Switching Period" (Inventor: John Melanson; Cirrus Docket No. 1674-IPD).

BACKGROUND OF THE INVENTION

Field of the Invention

(2) The present invention relates in general to the field of signal processing, and, more specifically, to apparatuses and methods for providing an adjustable constant current source which operates in both Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM).

DESCRIPTION OF THE RELATED ART

(3) Switch-mode systems are well known in the art. Figure 1 shows an exemplary switch-mode system 100. Switch-mode system 100 includes a switch-mode converter power stage 102, a converter current controller 104, and a load 106. Power 101 is fed into switch-mode converter power stage 102. Switch-mode system 100 utilizes switch-mode converter power stage 102 to convert alternating current (AC) voltages (such as line/mains voltages) to direct current (DC) voltages or DC-to-DC wherein the input current is proportional to the input voltage. Converter current controller 104 controls the current of switch-mode converter power stage 102, and switch-mode converter power stage 102 accordingly drives load 106. An exemplary switch-mode converter power stage 102 may be a buck converter or a boost converter. For switch-mode converter power stage 102, two modes of switching stage operation exist: Discontinuous Conduction Mode ("DCM") and Continuous Conduction Mode ("CCM").

(4) In CCM, the switch of switch-mode converter power stage 102 switches "ON" by converter current controller 104 when the inductor current i_L of converter current controller 104 is non-zero, and the current in the energy transfer inductor of converter current controller 104 never reaches zero during the switching cycle. Figure 2A shows exemplary target current i_{target} (for inductor current i_L) having a value of three (3) amp. Figure 2A further shows inductor current i_L has a period of ten (10) microsecond and is always non-zero in value. In CCM, the current swing is less than in DCM, which results in lower I^2R power losses and lower ripple current for inductor current i_L which results in lower inductor core losses. The lower voltage swing also reduces Electro Magnetic Interference (EMI), and a smaller input filter can then be used. Since the switch of switch-mode converter power stage 102 is turned "OFF" when the inductor current i_L is not equal to zero, the diode of switch-mode converter power stage 102 needs to be very fast in terms of reverse recovery in order to minimize losses. In DCM, a switch of switch-mode converter power stage 102 is turned on (e.g., "ON") by converter current controller 104 when the inductor current i_L of the inductor of switch-mode converter power stage 102 equals zero. Figure 2B shows exemplary target current i_{target} having a

value of 0.8 amp. Figure 2B further shows inductor current i_L has a period of ten (10) microsecond and does fall to the zero value at a portion of each period.

(5) As an example, for a switch-mode system 100 used to drive a Light Emitting Diode (LED) lighting system, it is important to have an accurate constant current output that is adjustable across a wide dynamic range, such as a range of one hundred-to-one (100:1). Such an accurate adjustable constant output requires a switch-mode converter power stage 102 that can smoothly transition between CCM and DCM and provide a controlled output in both CCM and DCM. For high target current values i_{target} that are set for inductor current i_L , the current ripple needs to be minimized. Such low current ripple generally calls for operation of the switch-mode converter power stage 102 to be in CCM. Unless the inductor of switch-mode converter power stage 102 is greatly oversized, switch-mode converter power stage 102 will operate in DCM at a lower average current i_{average} for inductor current i_L . If the current of switch-mode converter power stage 102 in CCM mode is controlled in such a way that the time above target current i_{target} and the time below that target current i_{target} are equal, then the average current i_{average} is equal to the target current i_{target} , assuming linear (non-saturating) operation of the inductor. CCM operation of switch-mode converter power stage 102 generally does not require knowing the inductor value L (or scaled inductor constant $F * L$ product wherein F may be an on-time period divided by the count value of the on-time period) nor the input/output ratio D in order to provide such accurate constant average current output.

(6) However, providing a smooth transition between CCM and DCM for a converter power stage 102 has its challenges. For example, in DCM, the inductor value L (or scaled inductor $F * L$ product) and input/output ratio D need to be known since they directly affect the current calibration. Any inaccuracy will cause a differential non-linearity ("DNL") error in the effective current Digital-to-Analog Converter ("DAC"). Thus, in order to provide at least a smoother transition between CCM and DCM, there are needs and desires to discover, observe, and/or derive the inductor value L (or scaled inductor constant $F * L$ product) and the input/output ratio D of a switch-mode converter system, particularly when the switch-mode converter system operates in DCM. The

attaining of such measurements allows the on-time or the total operating period for the switch of the switch-mode converter 102 to be controlled so that an accurate adjustable constant average current output for the inductor current i_L is provided.

SUMMARY OF THE INVENTION

(7) A converter system and method of operating a converter system are disclosed. The converter system comprises a converter power stage that can operate in a Discontinuous Conduction Mode (DCM) in a range of output currents and a Continuous Conduction Mode (CCM) in another range of output currents. The converter power stage includes at least an inductor with an inductor value and a control switch. The converter power stage provides an average current. A current controller is coupled to the converter power stage. When the converter power stage operates in DCM, the converter power stage provides the average current and the current controller is configured to measure the inductor value of the inductor. Furthermore, the current controller can also be configured to measure an input-to-output conversion ratio from the converter power stage.

BRIEF DESCRIPTION OF THE DRAWINGS

(8) The present invention may be better understood, and its numerous objects, features and advantages made apparent to those skilled in the art by referencing the accompanying drawings. The use of the same reference number throughout the several figures designates a like or similar element.

(9) Figure 1 depicts an exemplary switch-mode system.

(10) Figure 2A depicts exemplary current waveforms of inductor current i_L and target current i_{target} for switch-mode converter 102 operating in Continuous Conduction Mode ("CCM") shown at a time scale of 10 milliseconds.

(11) Figure 2B depicts exemplary current waveforms of inductor current i_L and target current i_{target} for switch-mode converter 102 operating in Discontinuous Conduction Mode ("DCM") shown at a time scale of 10 milliseconds.

- (12) Figure 3 depicts details of an exemplary switch-mode buck converter power stage controlled by a Light Emitting Diode ("LED") current controller for driving LEDs.
- (13) Figure 4 depicts details of an exemplary LED lighting controller that includes a target current generator and a LED current controller.
- (14) Figure 5 depicts an exemplary current waveform for inductor current i_L of exemplary switch-mode buck converter that is used to illustrate a first exemplary technique to provide an accurate constant average inductor current output when exemplary switch-mode buck converter power stage operates in DCM to help allow for a smooth transition of switch-mode buck converter power stage between CCM and DCM.
- (15) Figure 6 depicts details of another exemplary switch-mode buck converter power stage controlled by a LED current controller for driving LEDs.
- (16) Figure 7 depicts exemplary current waveforms for control signal CS_0 , inductor current i_L , and sense current i_{sense} of exemplary switch-mode buck converter power stage that are used to illustrate second and third exemplary techniques to each provide an accurate constant average inductor current output by exemplary switch-mode buck converter power stage operating in a hybrid Discontinuous Conduction Mode (DCM)/Continuous Conduction Mode (CCM) that uses double or more pulses in a switching period wherein the techniques help allow for a smooth transition of switch-mode buck converter power stage between CCM and DCM.

DETAILED DESCRIPTION

- (17) Figure 3 depicts details of an Light Emitting Diode ("LED") lighting system 300 having an exemplary switch-mode buck converter power stage 301 controlled by a Light Emitting Diode ("LED") current controller 310 for driving LEDs 308. LED lighting system 300 is an exemplary system illustrating an embodiment of the present invention, and the present invention is not in any way limited to an LED lighting system nor the use of a buck converter, LED current controller, and LEDs. The present invention can also

be used for other suitable applications as well as utilize other converters/converter power stages (e.g., boost converters) or controllers.

(18) Switch-mode buck converter power stage 301 comprises a control switch (e.g., Field Effect Transistor ("FET")) 302 having a source and drain coupled in series with an inductor 304 as shown in Figure 3. The source of FET 302 is coupled to a positive side of input voltage V_{in} . Diode 306 is coupled across the input voltage V_{in} in which a first end of a diode 306 is coupled between the drain of FET 302 and inductor 304 while a second end of diode 306 is coupled to a negative side of the input voltage V_{in} . A string of LEDs 308 is coupled across the output voltage V_{out} (e.g., coupled from the positive side to negative side of output voltage V_{out}). The string of LEDs 308 may, for example, include twenty (20) to one hundred (100) LEDs coupled together in series.

(19) An end of sense resistor R_{sense} is coupled to the negative side of input voltage V_{in} , and the other end of sense resistor R_{sense} is coupled to the second end of diode 306. Sense resistor R_{sense} is utilized to detect the sense current i_{sense} that is flowing through FET 302. For the sense current i_{sense} being provided to LED current controller 310 from a node that is at the drain of FET 302 as shown in Figure 3, the sense resistor R_{sense} can be located anywhere in the current loop 312. Alternatively, as shown in dotted lines, an end of sense resistor R_{sense} is coupled to the second end of diode 306, and the other end of sense resistor R_{sense} is coupled to the negative side of the output voltage V_{out} . For the sense current i_{sense} being provided to LED current controller 310 from a node that is at an input end of inductor 304 as shown in Figure 3, the sense resistor R_{sense} can be located anywhere in the current loop 314. LED current controller 310 outputs a switch control signal CS_0 which is fed into the gate of FET 302 and controls activation and deactivation of FET 302 as a switch.

(20) For example, the output voltage V_{out} of exemplary LED lighting system 300 at full brightness intensity can be at or around four hundred milliamperes (400 mA). Switch-mode buck converter power stage 301 operates in CCM when the output voltage V_{out} is at least fifty (50) to one hundred (100) milliamperes (50 to 100 mA). When the

output voltage V_{out} falls below 50 to 100 mA, switch-mode buck converter power stage 301 operates in DCM.

(21) In LED lighting system 300, the load inductor current i_L is always measurable, that is, the high side switch of FET 302 is measurable. Referring now to Figures 3 and 4, a target current generator 412 is coupled to the LED current controller 310 for feeding a target current i_{target} into LED current controller 310. Target current generator 412 and LED current controller 310 together make up LED lighting controller 400 as shown in Figure 4. LED current controller 310 includes a local power supply 402 which provides power to the various components of LED current controller 310. LED current controller 310 further includes a state machine 410 which receives the target current i_{target} that is fed in from target current generator 412. State machine 410 provides a digital signal that is reflective or representative of the target current i_{target} to digital-to-analog converter 404. DAC 404 converts the representative digital signal into a corresponding analog signal. The analog signal and the sense current i_{sense} are fed into comparator (COMP) 406 for comparison, and the result of the comparison is fed into state machine 410. LED current controller 310 further includes a clock (oscillator) 408, and clock (osc) 408 is coupled to and utilized by state machine 410. The techniques (e.g., first, second, and third techniques) of the present invention in providing an accurate adjustable constant average inductor current output i_{avg} when a converter operates in DCM are implemented in state machine 410. Furthermore, LED controller 310 may be implemented on a single integrated circuit (IC) or single IC substrate. Target current generator 412 may also be part of the single IC or may be external to the IC.

(22) Referring now to Figures 3 and 5, when a clock period of clock (oscillator) 408 of LED current controller 310 is started, FET 302 is turned on. A reference current i_{ref} is set at a suitable value, which is some pre-selected current value between zero and the peak current i_{peak} . Reference current i_{ref} is set at a value that can be accurately measured but allows the load inductor current i_L to ramp up to the peak current i_{peak} as well.

(23) Figure 5 depicts an exemplary current waveform 500 for inductor current i_L of exemplary switch-mode buck converter power stage 301 that is used to illustrate a first

exemplary technique to provide an accurate adjustable constant average inductor current output i_{avg} when exemplary switch-mode buck converter operates in DCM. First exemplary technique help allow for a smooth transition of switch-mode buck converter power stage between CCM and DCM. As shown in Figure 5, when the load inductor current i_L reaches the reference current i_{ref} at time T_A , the first on time period T_1 is determined. In other words, time period T_1 is the time from when FET 302 turns on and when the load inductor i_L reaches the reference current i_{ref} . FET 302 is turned off at time $n * T_A$. Thus, the second on time period T_2 is determined from when the FET 302 is on at the time when the load inductor i_L reaches the reference current i_{ref} (e.g., at time T_A) to when the load inductor i_L reaches the peak current i_{peak} (e.g., at time $n * T_A$). n is a ratio and is preferably selected to be a ratio of 2 (e.g., 2:1). Load inductor current i_L decreases in value passing through reference current i_{ref} and falls to zero at time T_B . The off time period T_3 is defined from when the load inductor i_L reaches the peak current i_{peak} (e.g., at time $n * T_A$) until when the load inductor i_L reaches zero (e.g., at time T_B). The total period for inductor current i_L in Figure 5 is defined as time period TT . In this embodiment of LED lighting system 300, both the on time T_{on} (which is equal to time periods $T_1 + T_2$) and off time T_{off} (which is equal to time period T_3) can be observed or measured, but only the on period T_{on} and total period TT can be controlled. Therefore, in implementing the LED lighting system 300, either the on period T_{on} or total period TT is controlled in order to provide an accurate constant average current output i_{avg} for inductor current i_L .

(24) The input/output ratio D and the ratio CI involving the inductor value (inductance) L for inductor 304 can be measured and/or determined from the following mathematical relationships:

$$(25) \quad \text{Peak current } i_{peak} = T_{on} * (V_{in} - V_{out})/L \quad \text{Equation A}$$

$$(26) \quad \text{Off time period } T_{off} = ((V_{in} - V_{out})/V_{out}) * T_{on} \quad \text{Equation B}$$

$$(27) \quad D = V_{out}/V_{in} = T_{on} / (T_{on} + T_{off}) \quad \text{Equation C}$$

$$(28) \quad \text{Reference current } i_{ref} = T_1 * (V_{in} - V_{out})/L \quad \text{Equation D}$$

$$(29) \quad \text{Ratio } C1 = i_{\text{ref}}/T_1 = (V_{\text{in}} - V_{\text{out}})/L \quad \text{Equation E}$$

(30) With respect to the present invention, the measuring and determination of inductor value (inductance) L for inductor 304 is not in any way limited to the measurement and determination of the actual inductance of inductor 304 (e.g., measured in milli-Henries) but can be a measurement or determination of any value that is representative or reflective of the inductance value. For example, such a representative or reflective value may be in conformity with a mathematical rate of increase related to the inductance, a scaled version of the inductance, a binary format of the inductance, or a direct, indirect or inverse proportional relationship to the inductance (e.g., L ; $1/L$, etc.).

(31) Ratio $C1$ provides a relationship in which the inductor value L is determined based on the rate of rise (e.g., i_{ref}/T_1) of the current when FET 302 is switched on. The input-to-output conversion ratio D for converter 301 is calculated from an on time (ramp-up time) $T_{\text{on}} (= T_1 + T_2)$ of inductor current i_L and an off-time (ramp-down time) $T_{\text{off}} (= T_3)$ of inductor current i_L . Since the above values can be determined, the average constant output inductor current i_{AVG} for inductor current i_L is determined as follows:

$$\begin{aligned} i_{\text{AVG}} &= i_{\text{peak}}/2 * ((T_{\text{on}} + T_{\text{off}})/TT) & \text{Equation F} \\ &= (T_{\text{on}} * (V_{\text{in}} - V_{\text{out}})/L)/2 * ((T_{\text{on}} + ((V_{\text{in}} - V_{\text{out}})/V_{\text{out}}) * T_{\text{on}})/TT) \\ &= T_{\text{on}}^2/2 * (V_{\text{in}} - V_{\text{out}})/L * (1 + (V_{\text{in}} - V_{\text{out}})/V_{\text{out}}) / TT \\ &= T_{\text{on}}^2/2 * (V_{\text{in}} - V_{\text{out}})/L * (V_{\text{in}}/V_{\text{out}}) * (1/TT) \\ &= T_{\text{on}}^2/2 * C1/D * (1/TT) \end{aligned}$$

(32) On time T_{on} can be determined and respectively controlled as follows:

$$T_{\text{on}} = \text{Square Root } (2 * i_{\text{AVG}} * D / C1 * TT) \quad \text{Equation G}$$

(33) As shown in Equation G, on time T_{on} for FET 302 can be controlled for providing a given adjustable average constant output inductor current i_{AVG} for inductor current i_L by using the measured, determined, and/or known values for the input/output ratio D , the ratio $C1$, and the total period TT of inductor current i_L .

(34) Figure 6 depicts details of another Light Emitting Diode ("LED") lighting system 600 having another exemplary switch-mode buck converter power stage 601 controlled by a Light Emitting Diode ("LED") current controller 310 for driving LEDs 308. Figure 6 also shows LED current controller 310 coupled to target current generator 412, and as mentioned before, when Figure 4 was discussed earlier, target current generator 412 and LED current controller 310 make up LED lighting controller 400. LED lighting system 600 is another exemplary system illustrating another embodiment of the present invention, and the present invention is not in any way limited to an LED lighting system nor the use of a buck converter power stage, LED current controller, and LEDs. The present invention can also be used for other suitable applications as well as utilize other converters/converter power stages (e.g., boost converters) or controllers.

(35) Switch-mode buck converter power stage 601 comprises LEDs 308, inductor 304, FET (control switch) 302, and sense resistor R_{sense} coupled in series together and across the output voltage V_{out} as shown in Figure 6. One end of diode 306 is coupled to a positive side of input voltage V_{in} , and the other end of diode 306 is coupled at a node between inductor 304 and FET 302 as shown in Figure 6. Output current i_{out} is shown flowing at the positive side of output voltage V_{out} . Inductor current i_L flows through inductor 304 while sense current i_{sense} flows through resistor R_{sense} . Again, sense resistor R_{sense} is utilized to detect the sense current i_{sense} that is flowing through FET 302. LED current controller 310 outputs a switch control signal CS_0 which is fed into the gate of FET 302 and controls activation and deactivation of FET 302 as a switch. Switch-mode buck converter power stage 601 can only allow the measuring or detecting of the inductor current i_L when FET 302 is on and cannot allow the measuring or detecting of inductor current i_L when FET 302 is off. Thus, switch-mode buck converter power stage 601 requires sense current i_{sense} only when FET 302 is on, and the low side switch 302 can be used for sensing sense current i_{sense} .

(36) Referring now to Figure 7, exemplary current waveforms 700, 702, and 704 for respective control signal CS_0 , inductor current i_L , and sense current i_{sense} of exemplary switch-mode buck converter power stage 601 that are used to illustrate second and third exemplary techniques to each provide an accurate adjustable constant average inductor

current output i_{avg} by exemplary switch-mode buck converter 601 operating in a hybrid Discontinuous Conduction Mode (DCM)/Continuous Conduction Mode (CCM) that uses double or more pulses in a switching period. The techniques help allow for a smooth transition of switch-mode buck converter power stage between CCM and DCM. U.S. Application Serial Number 12/113,536 (hereafter '536 patent application) filed on May 1, 2008 entitled "Switch-Mode Converter Operating in a Hybrid Discontinuous Conduction Mode (DCM)/Continuous Conduction Mode (CCM) That Uses Double or More Pulses in a Switching Period" (Inventor: John Melanson; Cirrus Docket No. 1674-IPD) discusses in detail the operation of a switch-mode converter in such hybrid DCM/CCM that uses double or more pulses in a switching period, and the '536 patent application is hereby incorporated by reference.

(37) Referring now to waveforms 700, 702, and 704 of Figure 7, a second exemplary technique for providing an accurate adjustable constant average inductor current output i_{avg} by exemplary switch-mode buck converter power stage 601 is discussed. Control signal CS_0 transitions to a high value and turns on FET 302 during time period T_1 . Inductor current i_L ramps up and crosses through reference current i_{ref} and reaches peak current i_{peak} at the end of period T_1 . Sense current i_{sense} ramps up to a peak sense current value during time period T_1 . During time period T_2 , control signal CS_0 goes to a low value and turns off FET 302. During this time period T_2 , switch-mode buck converter 601 cannot allow the detection of the value of inductor current i_L , and sense current i_{sense} discharges to a zero value. Control signal CS_0 next goes back to a high value and turns on FET 302 during time period T_3 . Inductor current i_L ramps back up and crosses through reference current i_{ref} and reaches peak current i_{peak} again. During this time period T_3 , switch-mode buck converter power stage 601 can allow the value of inductor current i_L to be detected, and sense current i_{sense} ramps up to a peak sense current value. Control signal CS_0 then goes back to a low value and turns off FET 302 during time period T_4 . Inductor current i_L ramps down to zero during time period T_4 . During this time period T_4 , switch-mode buck converter power stage 601 cannot allow for the detection of the value of inductor current i_L , and sense current i_{sense} discharges to a zero value.

(38) If time period T_3 is less than time period T_1 , switch-mode buck converter power stage 601 has then entered into the hybrid DCM/CCM that uses double or more pulses in a switching period. However, if time period T_3 is approximately equal to time period T_1 , then time period T_2 needs to be adjusted (e.g., decreased) so that time period T_3 will be less than time period T_1 .

(39) Referring now to Figure 7, the total charge in a normal single pulse for inductor current i_L would involve a normal switching time period that includes the time periods T_1 and T_4 only. The total charge for a single pulse would be the total charge Q_1 during time period T_1 and the total charge Q_2 during time period T_4 . Thus, this relationship for the total charge of a normal single pulse is represented by the following mathematical relationship:

$$\text{Total charge } Q_{\text{single}} = Q_1 + Q_2 = (T_1 + T_4) * i_{\text{peak}} / 2 \quad \text{Equation H}$$

(40) However, inductor current i_L cannot be observed or measured during time period T_4 . Thus,

$$T_4 / T_1 = T_2 / T_3 \quad \text{Equation I}$$

$$T_4 = T_1 / T_3 * T_2 \quad \text{Equation J}$$

(41) The double or more pulses of a switching period for inductor current i_L as shown in current waveform 702 is basically an overlap of two single pulses (e.g., each involving time periods T_1 and T_4 only). The overlap charge area A1 being a triangular area as shown in current waveform 702. The left side length of the overlap charge area A1 is reflective of the difference between time periods T_1 and T_3 while the right side length of the overlap charge area A1 is reflective of the difference between time periods T_4 and T_2 . Thus, the total charge Q_T under current waveform 702 is calculated as follows:

$$\text{Total Charge } Q_T = 2 * Q_{\text{single}} - A1 \quad \text{Equation K}$$

$$\text{Overlap charge area } A1 = ((T_1 - T_3) / T_1) * Q_1 + ((T_4 - T_2) / T_4) * Q_2$$

(42) As shown in Figure 7, peak current i_{peak} is set equal to 1 Amp, and in the exemplary waveforms of Figure 7, the geometry and triangular areas are set up to be the

same as each other so that $T_1 = T_4$ and $T_3 = T_2$, and the mathematical relationships can be simplified.

$$\begin{aligned}
 \text{Overlap charge area } A1 &= ((T_1 - T_3) / T_1) * Q_1 + ((T_1 - T_3) / T_1) * Q_2 \quad \text{Equation L} \\
 &= (Q_1 + Q_2) * ((T_1 - T_3) / T_1)^2 \\
 &= Q_{\text{single}} * ((T_1 - T_3) / T_1)^2 \\
 &= Q_{\text{single}} * (1 - 2 * T_3 / T_1 + (T_3 / T_1)^2)
 \end{aligned}$$

$$\begin{aligned}
 \text{Total Charge } Q_T &= 2 * Q_{\text{single}} - (Q_{\text{single}} * (1 - 2 * T_3 / T_1 + (T_3 / T_1)^2)) \quad \text{Equation M} \\
 &= Q_{\text{single}} + 2 * T_3 / T_1 * Q_{\text{single}} - (T_3 / T_1)^2 * Q_{\text{single}} \\
 &= Q_{\text{single}} * (1 + 2 * T_3 / T_1 - (T_3 / T_1)^2) \\
 &= i_{\text{peak}} / 2 * (T_1 + T_4) * (1 + 2 * T_3 / T_1 - (T_3 / T_1)^2) \\
 &= i_{\text{peak}} / 2 * (T_1 + T_1 / T_3 * T_2) * (1 + 2 * T_3 / T_1 - (T_3 / T_1)^2)
 \end{aligned}$$

$$\begin{aligned}
 i_{\text{avg}} &= \text{Total Charge } Q_T / TT \quad \text{Equation N} \\
 &= i_{\text{peak}} / 2 * (T_1 + T_1 / T_2 * T_3) * (1 + 2 * T_3 / T_1 - (T_3 / T_1)^2) / (T_1 + T_2 + T_3 + T_4) \\
 &= i_{\text{peak}} / 2 * (T_1 + T_1 / T_2 * T_3) * (1 + 2 * T_3 / T_1 - (T_3 / T_1)^2) / (T_1 + T_2 + T_3 + T_1 / T_3 * T_2)
 \end{aligned}$$

(43) Since time period T_1 is measured, time period T_2 is preset (e.g., by the user), time period T_3 is measured, the waiting time period T_4 can be derived from time periods T_1 , T_2 , and T_3 , the peak current i_{peak} is known, the average current i_{avg} can be calculated and determined by Equation N above. If the T_1 / T_2 ratio is chosen as a power of two, then the match is simple. From the time periods T_1 , T_2 , and T_3 , the calculation of the total charge $Q_T = (i_{\text{avg}} * TT)$ becomes straight forward. Enough pulses based on the known time periods T_1 , T_2 , and T_3 can be created to set any value for average current i_{avg} , and thus, control of a constant average output current i_{avg} can be provided.

(44) Since time period T_4 can be derived and known, a number of single pulses (e.g., with ramp-up time period T_1 and ramp-down time period T_4) can be used to provide respective average currents. Double or more pulses for a switching period can be used constantly, occasionally (to update the $D = \text{input/output ratio}$), or in any frequency manner with the single pulses.

(45) In this second exemplary technique, ratio $C1$ as discussed for the first exemplary technique provides the same relationship in which the inductor value L is determined based on the rate of rise (e.g., i_{ref}/T_1) of the current when FET 302 for converter 601 is switched on. The input-to-output conversion ratio D for converter 601 is calculated from a total on time (ramp-up time) $T_{\text{on}} (= T_1 + T_3)$ of inductor current i_L and a total off-time (ramp-down time) $T_{\text{off}} (= T_2 + T_4 = T_2 + T_1 / T_3 * T_2)$ of inductor current i_L . This second exemplary technique reflects the fact that the FET 302 is turned on again at least for a second time within the switching period TT before inductor current i_L decays to zero.

(46) Referring again to waveforms 700, 702, and 704 of Figure 7, a third exemplary technique for providing an accurate adjustable constant average inductor current output i_{avg} by exemplary switch-mode buck converter power stage 601 is further discussed. The third exemplary technique is identical to the second exemplary technique except that at the end of timing period T_4 , an additional compensating pulse (shown in dotted line) having an on time of time period $T_5 = T_1 - T_3$ is triggered for control signal CS_0 as shown in current waveform 700. A single triangular pulse with a known charge area of $A1$ (e.g., identical to the overlap charge area $A1$) results since time periods T_1 and T_3 are known, and the single triangular pulse is added in the current waveform 702 for inductor current i_L . The mathematical calculations become further simplified since the total charge Q_T is determined by:

$$\text{Total Charge } Q_T = 2 * Q_{\text{single}} - A1 + A1 = 2 * Q_{\text{single}} \quad \text{Equation O}$$

(47) Therefore, the principles and techniques of the present invention help allow for a smooth transition of a converter power stage operate between CCM and DCM. When converter power stage 301 or 601 operates in DCM, converter power stage 301 or 601 is able to provide an average constant output current that is adjustably controlled by an

inductor value that is measured and/or detected and further controlled by an input-to-output conversion ratio that is measured and/or detected. The exemplary techniques of the present invention allow the inductor value (e.g., inductor value L) and the input-to-output conversion ratio (e.g., input-to-output ratio D) to be accurately measured, determined, or discovered. Accuracy in determining the inductor value and/or the input-to-output ratio for a converter directly affect the current calibration and will help avoid or minimize differential non-linearity ("DNL") errors in the effective current Digital-to-Analog Converter ("DAC"). Thus, it is important to provide an accurate adjustable constant average current output for the inductor current i_L of a switch-mode converter, especially when the switch-mode converter is operating in DCM. The present invention provides ways to provide such a constant current output.

(48) Although the present invention has been described in detail, it should be understood that various changes, substitutions and alterations can be made hereto without departing from the spirit and scope of the invention as defined by the appended claims.

WHAT IS CLAIMED IS:

1. A converter system, comprising:
a converter power stage that can operate in a Discontinuous Conduction Mode (DCM) in a range of output currents and a Continuous Conduction Mode (CCM) in another range of output currents wherein the converter power stage includes at least an inductor with an inductor value and a control switch and the converter power stage provides an average current, and
a current controller coupled to the converter power stage; and
wherein when the converter power stage operates in DCM, the converter power stage provides the average current and wherein the current controller is configured to measure the inductor value of the inductor.
2. The converter system according to Claim 1, wherein the inductor value is determined from a rate of rise of an inductor current through the inductor when the control switch is on.
3. The converter system according to Claim 1 wherein the current controller is configured to measure an input-to-output conversion ratio from the converter power stage.
4. The converter system according to Claim 3, wherein the input-to-output conversion ratio is determined from a ramp-up time of the inductor current and a ramp-down time of the inductor current.
5. The converter system according to Claim 3, wherein a sense current is detected at the control switch and wherein the input-to-output conversion ratio is determined by turning the control switch on at least a second time within a switching period before the inductor current decays to zero.

6. The converter system according to Claim 5, wherein at least one additional pulse is triggered after the inductor current decays to zero so that a total charge for the inductor current over the switching period is a simple multiple of a charge for a normal single pulse over a normal switching period for the inductor current.
7. The converter system according to Claim 1, wherein the converter power stage is a switch-mode buck converter power stage.
8. The converter system according to Claim 7, wherein an output of the switch-mode buck converter power stage is coupled to and drives a light emitting diode (LED) load.
9. A method of operating a converter system, comprising:
 - operating a converter power stage in a Discontinuous Conduction Mode (DCM) in a range of output currents and a Continuous Conduction Mode (CCM) in another range of output currents in which the converter power stage includes at least an inductor with an inductor value and a control switch;
 - providing, by the converter power stage, an average current;
 - controlling, by a current controller, a current in the converter power stage; and
 - when the converter power stage operates in DCM, providing, by the converter power stage, the average current and configuring the current controller to measure the inductor value of the inductor .
10. The method according to Claim 9, further comprising:
 - determining the inductor value from a rate of rise of an inductor current through the inductor when the control switch is on.

11. The method according to Claim 9, further comprising:
configuring the current controller to measure an input-to-output conversion ratio from the converter power stage.
12. The method according to Claim 11, further comprising:
determining the input-to-output conversion ratio from a ramp-up time of the inductor current and a ramp-down time of the inductor current.
13. The method according to Claim 11, further comprising:
detecting a sense current at the control switch; and
determining the input-to-output conversion ratio by turning the control switch on at least a second time within a switching period before the inductor current decays to zero.
14. The method according to Claim 13, wherein determining the input-to-output ratio further comprises:
triggering at least one additional pulse after the inductor current decays to zero so that a total charge for the inductor current over the switching period is a simple multiple of a charge for a normal single pulse over a normal switching period for the inductor current.
15. The method according to Claim 9, wherein operating a converter power stage further comprises operating a switch-mode buck converter power stage.
16. The method according to Claim 15, further comprising:
coupling an output of the switch-mode buck converter power stage to a light emitting diode (LED) load and driving the LED load.

17. A current controller for controlling an inductor current of a converter power stage wherein the converter power stage includes at least an inductor with an inductor value and a control switch and can operate in a Discontinuous Conduction Mode (DCM) in a range of output currents and a Continuous Conduction Mode (CCM) in another range of output currents; comprising:

a local power supply, a state machine, a digital-to-analog converter, a comparator, and a clock coupled together in an operable manner, wherein the state machine receives a target current and the comparator compares a sense current from the converter with the target current, and the comparison is fed to the state machine to respectively provide a control signal to the switch;

the state machine is able to receive and measure from the converter power stage the inductor value so that the converter power stage is able to provide an average current of the converter power stage when the converter power stage operates in DCM.

18. The current controller according to Claim 17, wherein the inductor value is able to be determined from a rate of rise of an inductor current through the inductor when the control switch is on.

19. The current controller according to Claim 17, the state machine is able to receive and measure from the converter power stage an input-to-output conversion ratio.

20. The current controller according to Claim 19, wherein the input-to-output conversion ratio is able to be determined from a ramp-up time of the inductor current and a ramp-down time of the inductor current.

21. The current controller according to Claim 19, wherein a sense current is able to be detected at the control switch and wherein the input-to-output conversion ratio is able to be determined by turning the control switch on at least a second time within a switching period before the inductor current decays to zero.

22. The current controller according to Claim 21, wherein at least one additional pulse is triggered after the inductor current decays to zero so that a total charge for the inductor current over the switching period is a simple multiple of a charge for a normal single pulse over a normal switching period for the inductor current.

23. The current controller according to Claim 17, wherein the current controller is a light emitting diode (LED) current controller.

24. The current controller according to Claim 17, wherein the current controller is implemented in a single integrated circuit.

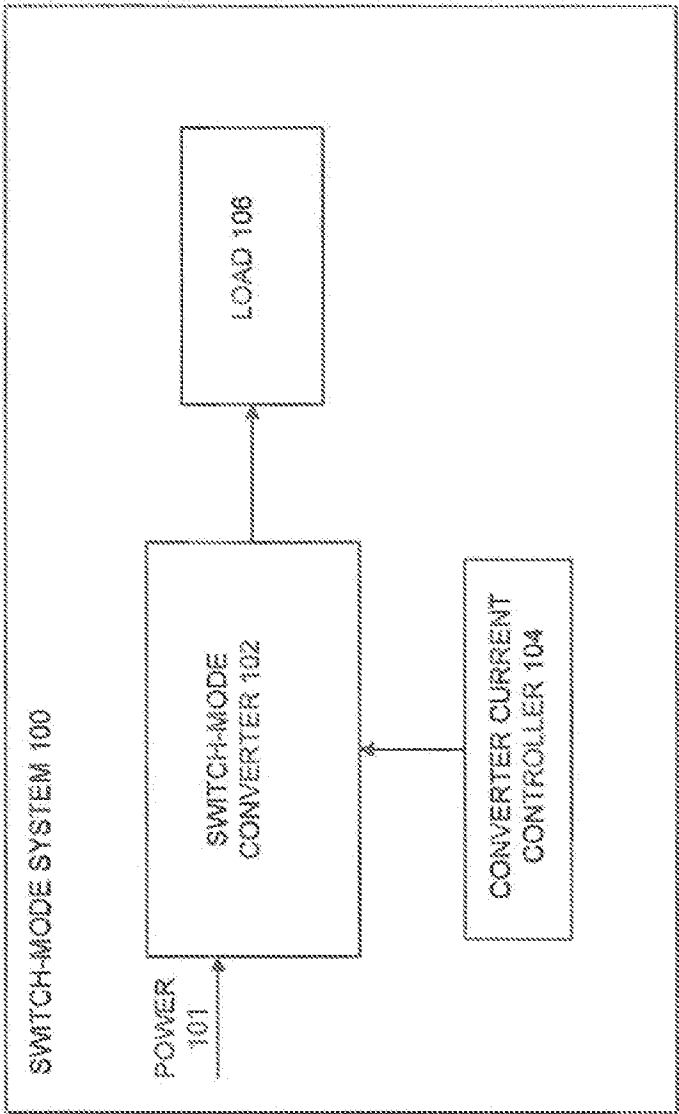


Figure 1

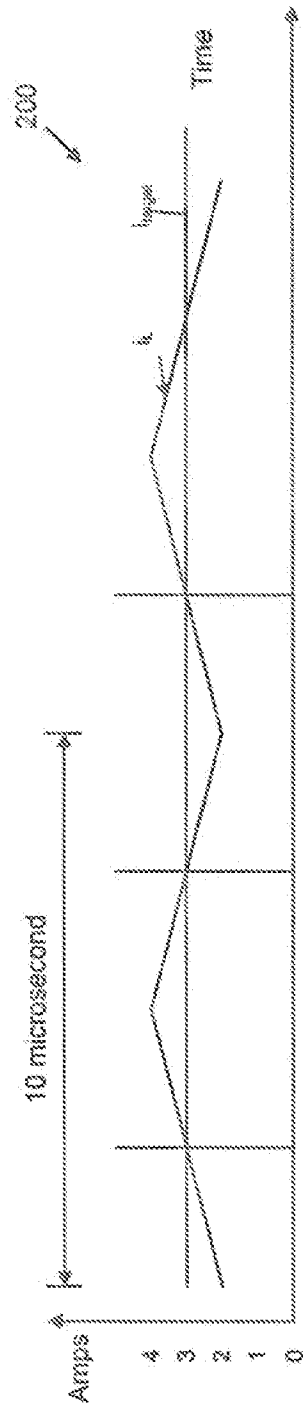


Figure 2A

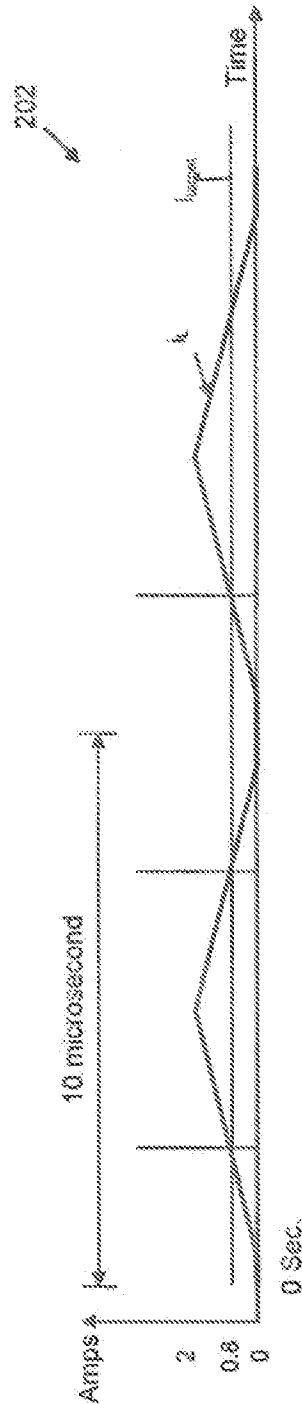


Figure 2B

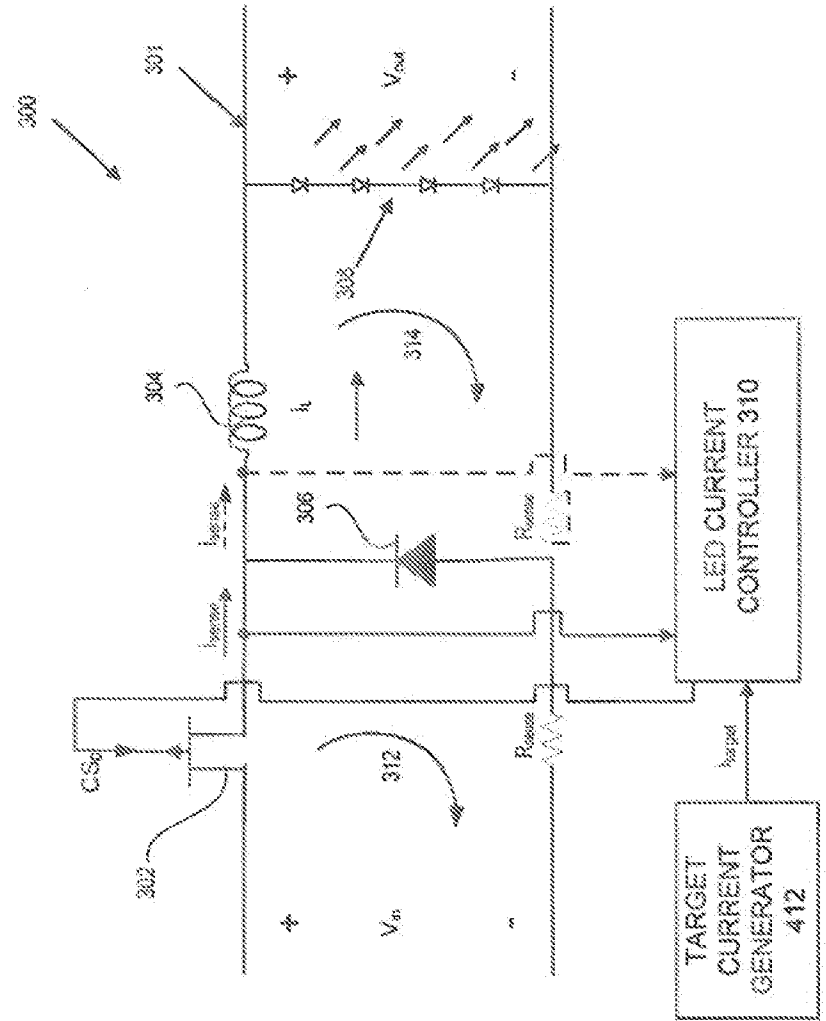


Figure 3

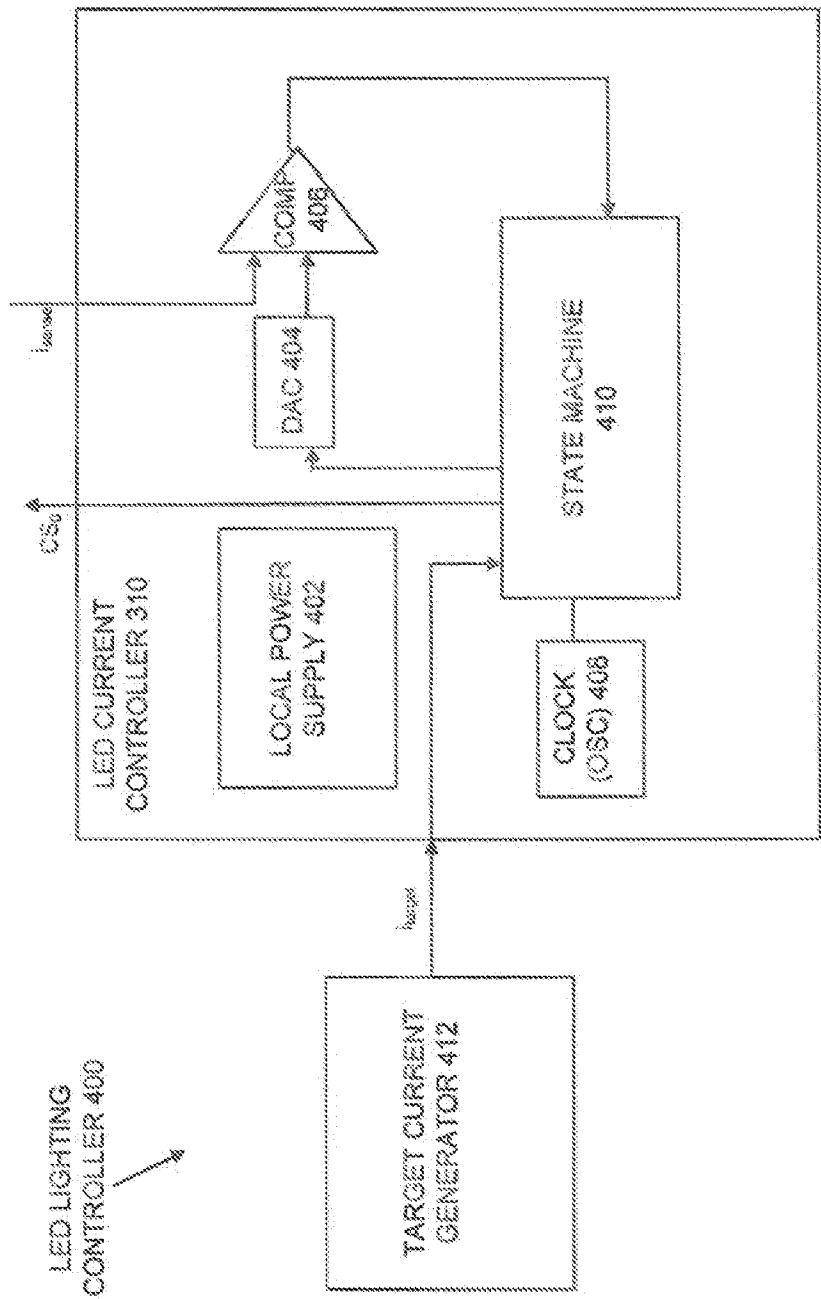
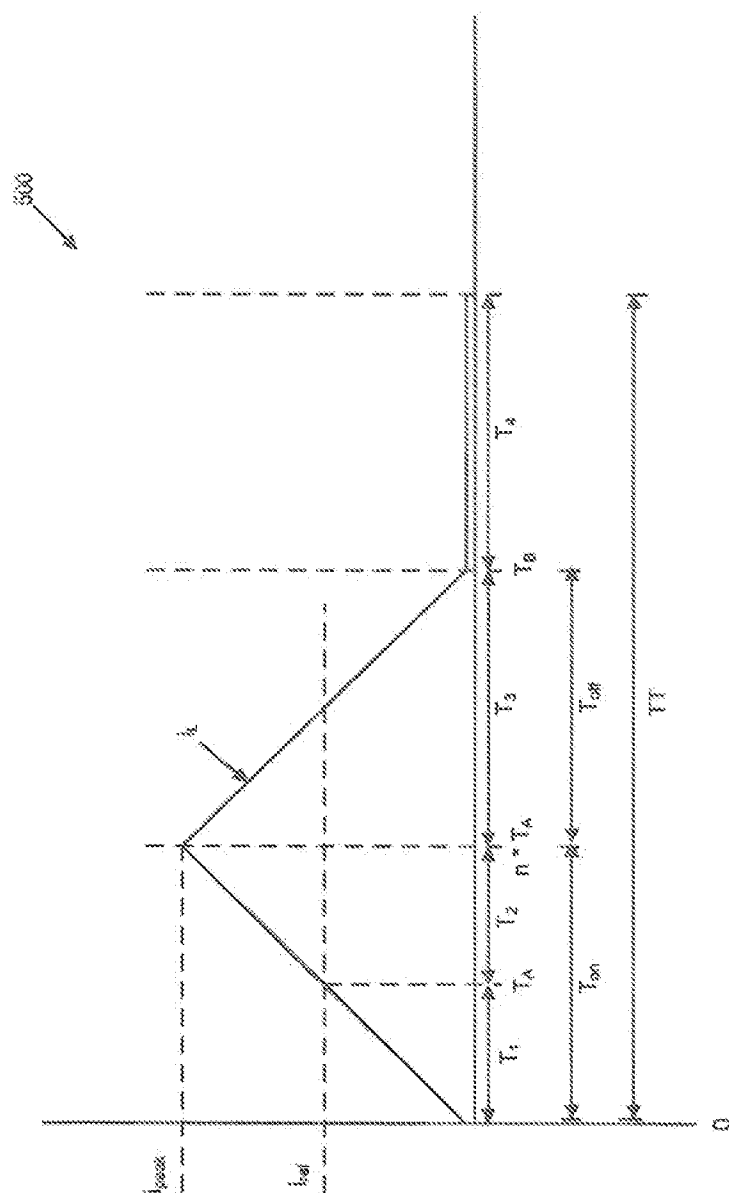


Figure 4



2000

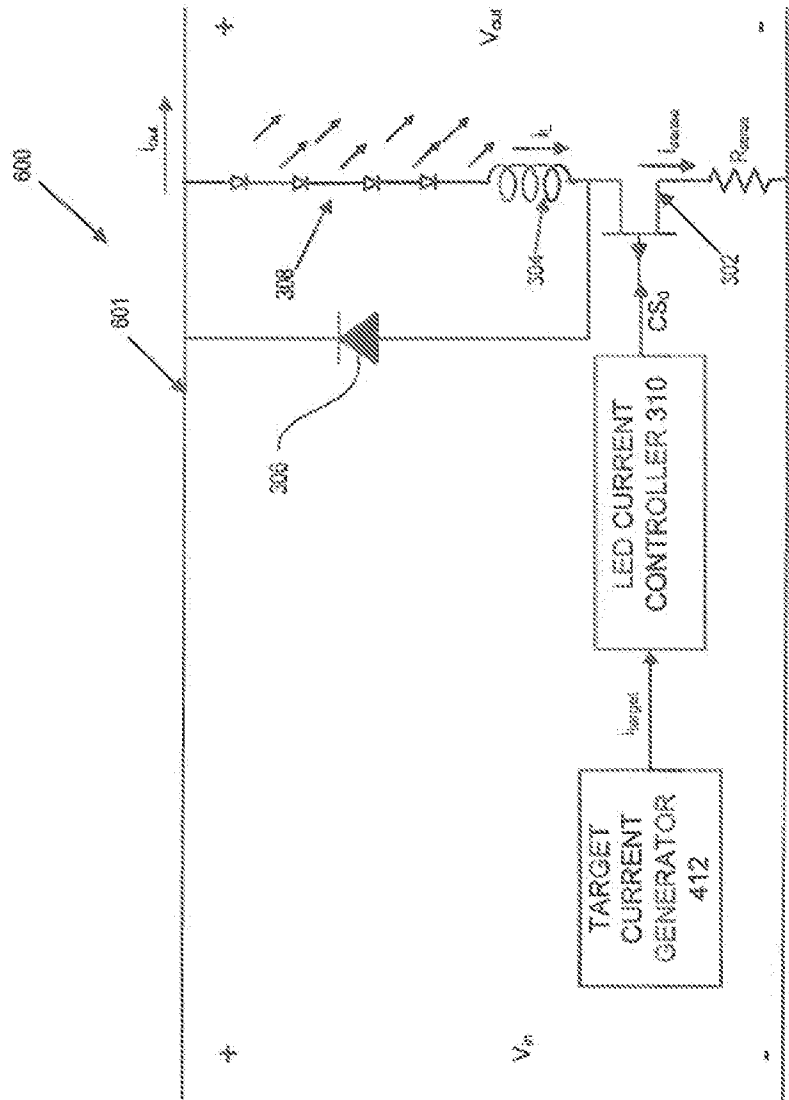


Figure 6

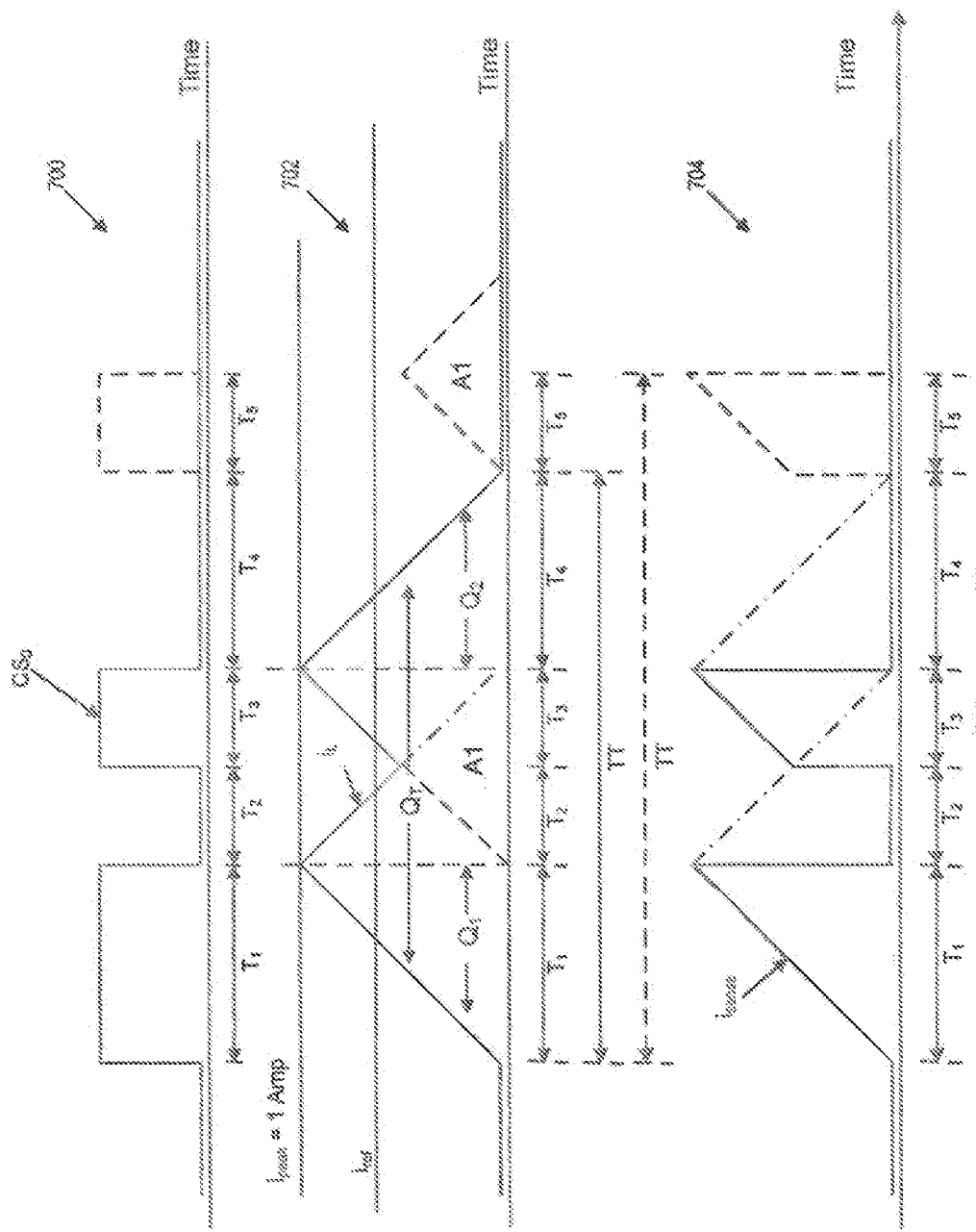


Figure 7