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(54) **POWER CONTROL SYSTEM FOR CURRENT REGULATED LIGHT SOURCES**

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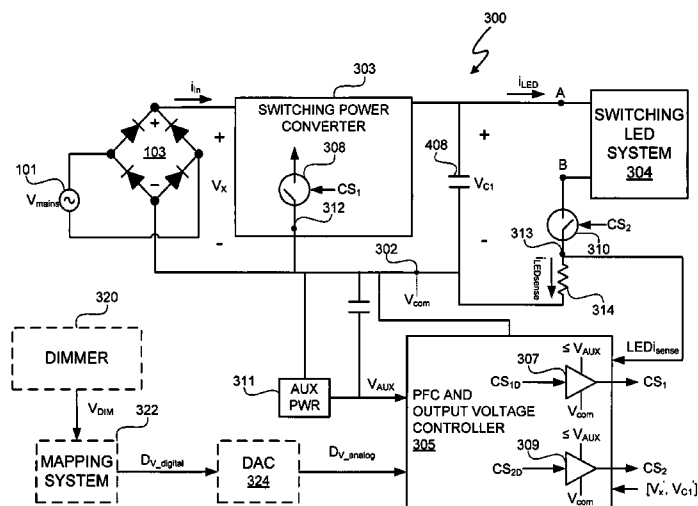See application file for complete search history.

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(57)   **ABSTRACT**

A light emitting diode (LED) lighting system includes a PFC and output voltage controller and a LED lighting power system. The controller advantageously operates from an auxiliary voltage less than a link voltage generated by the LED lighting power system. The common reference voltage allows all the components of lighting system to work together. A power factor correction switch and an LED drive current switch are coupled to the common reference node and have control node-to-common node, absolute voltage that allows the controller to control the conductivity of the switches. The LED lighting system can utilize feed forward control to concurrently modify power demand by the LED lighting power system and power demand of one or more LEDs. The LED lighting system can utilize a common current sense device to provide a common feedback signal to the controller representing current in at least two of the LEDs.

30 Claims, 15 Drawing Sheets

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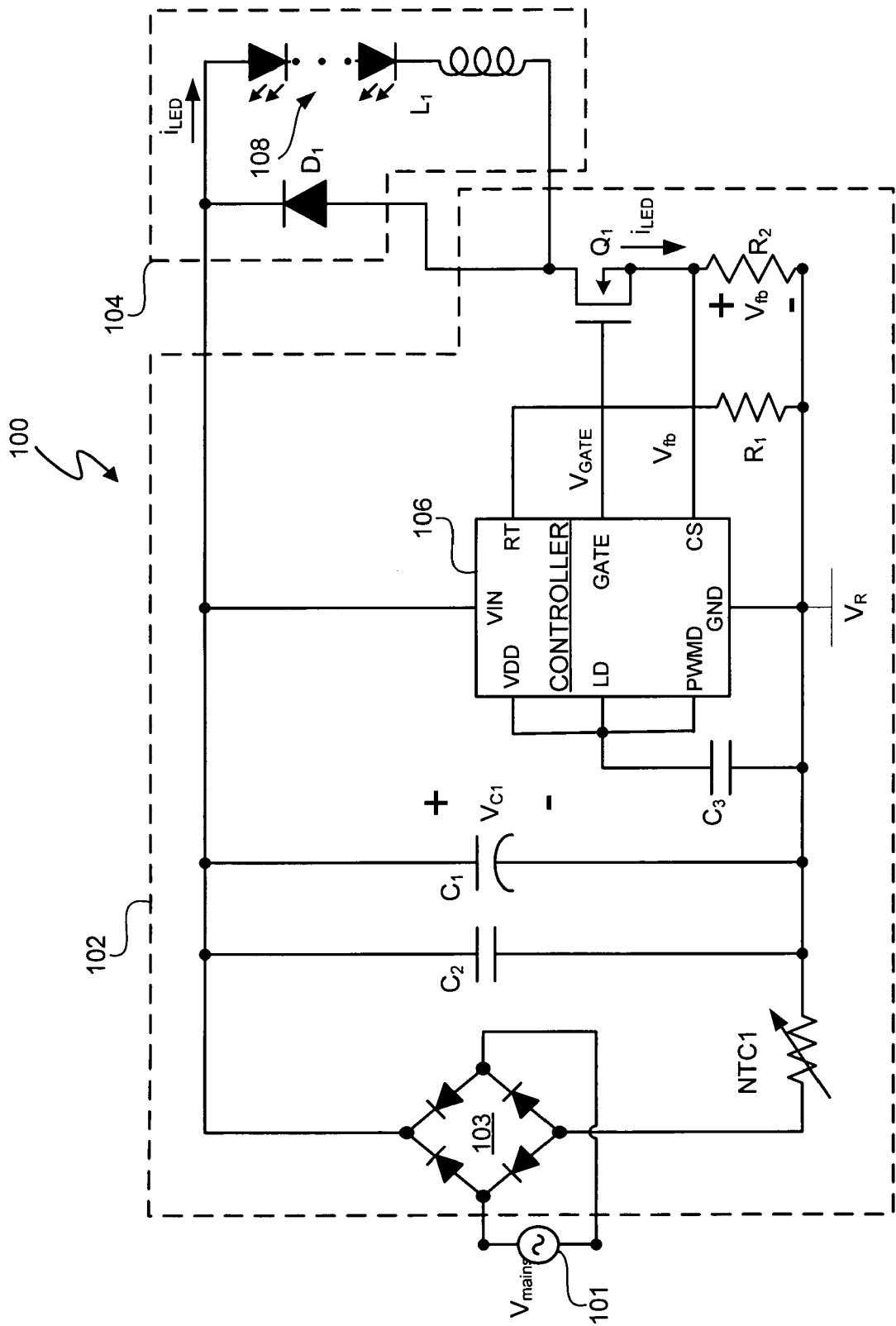
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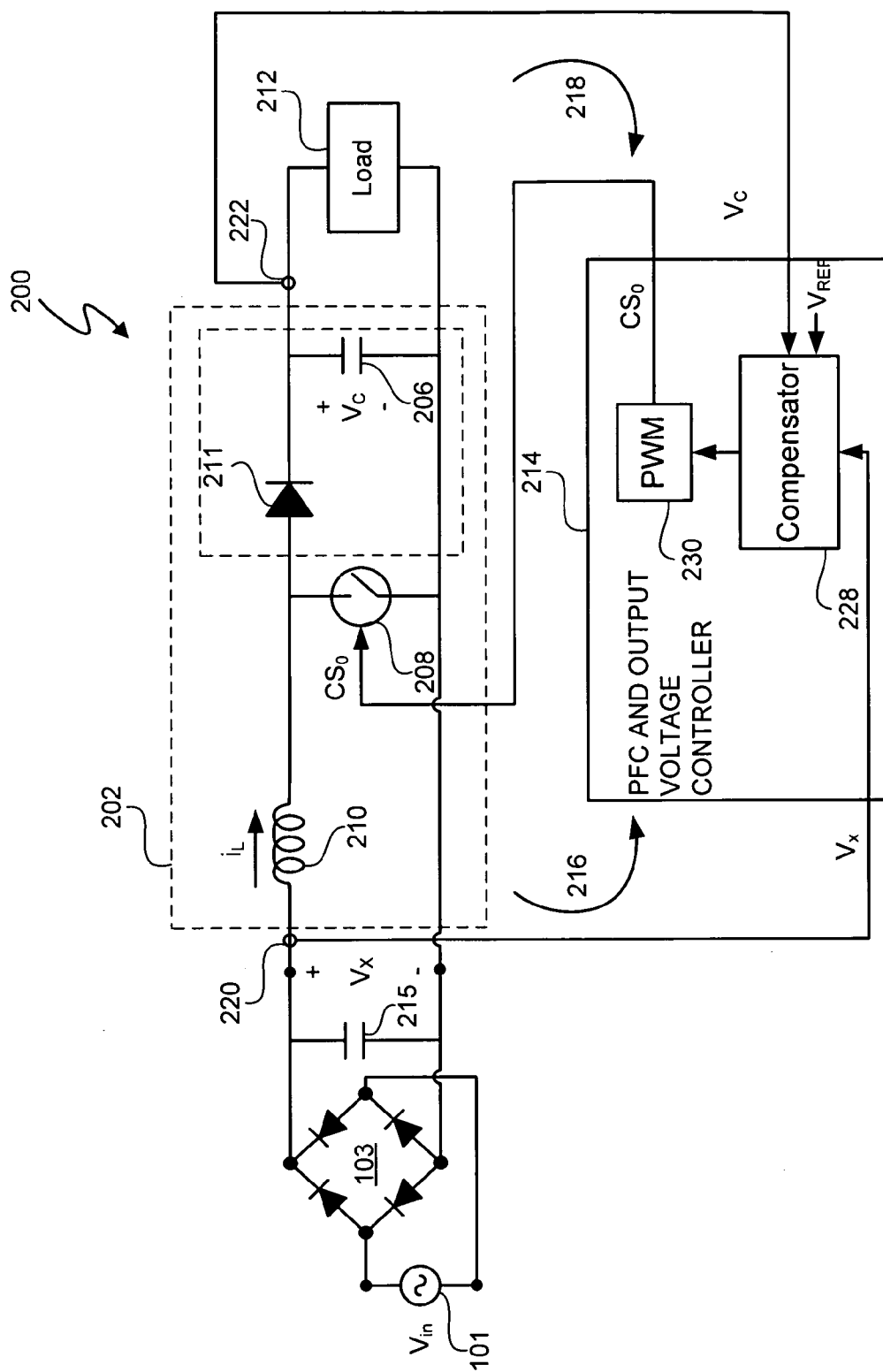
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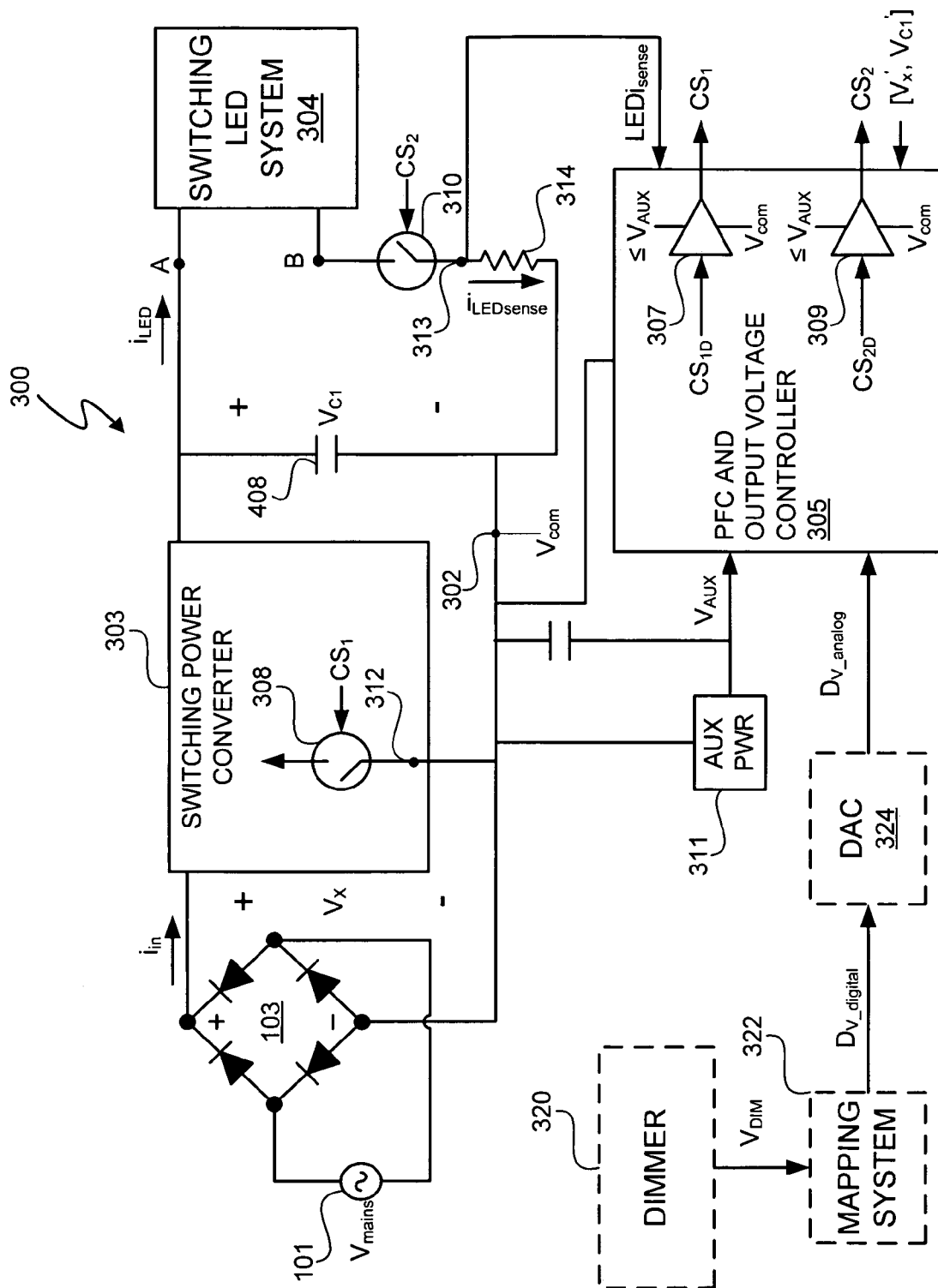
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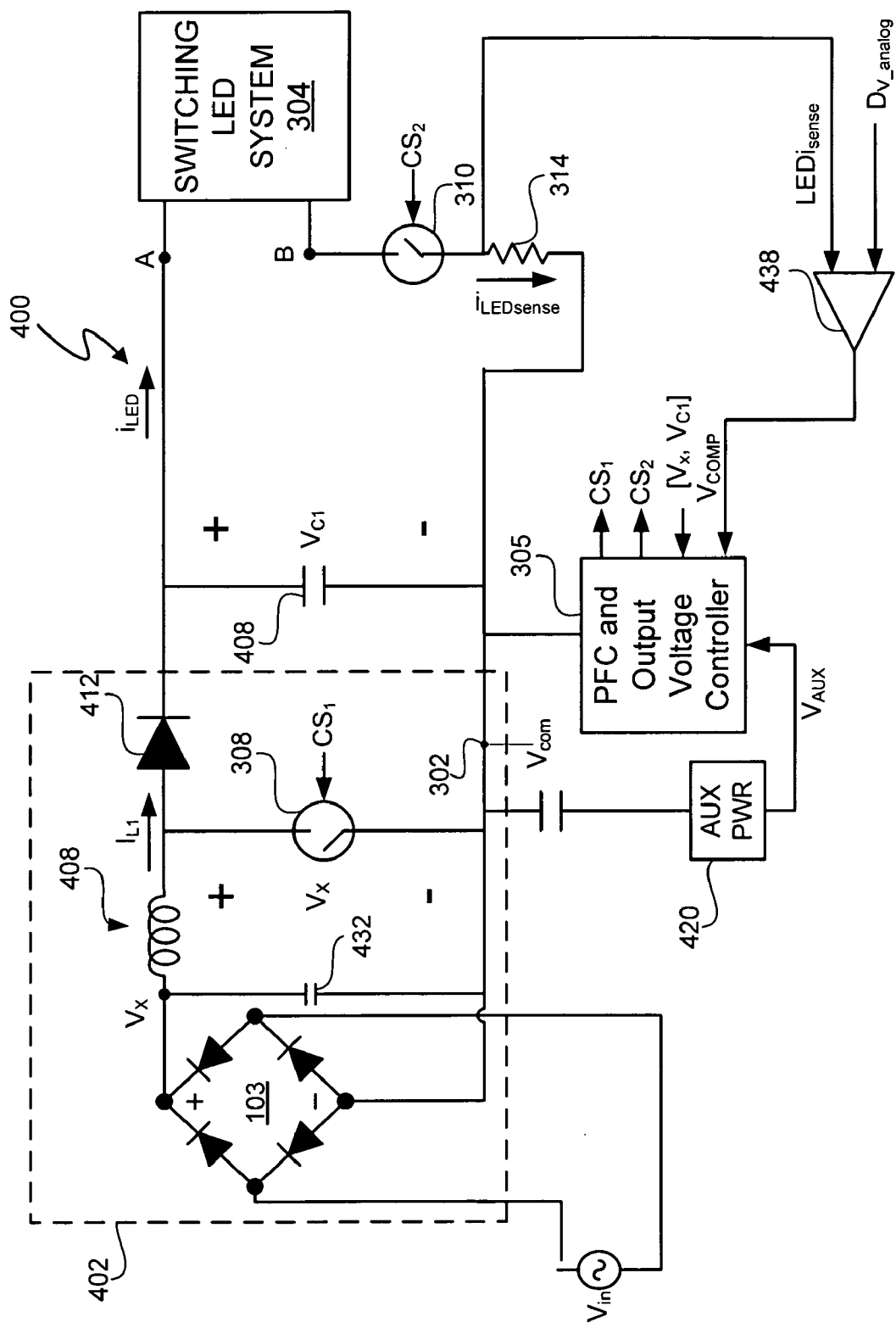
Figure 4

540

Figure 5B

530

Figure 5A

570

CS_x

$\leq V_{AUX}$

V_{com}

572

576

574

CS_x

Figure 5E

560

Figure 5D

550

Figure 5C

Figure 6B

Figure 6A

700

V_{comp}

CS_2

400

DIMMING LEVEL
INDICATED BY D_v

300

$i_{LEDsense}$

200

DIMMING LEVEL
INDICATED BY D_v

100

e.g. 10 micro-
seconds

T_1

$\sim T_1$

Time
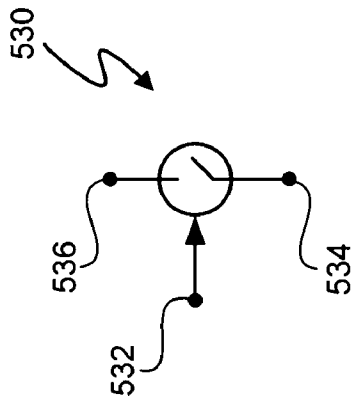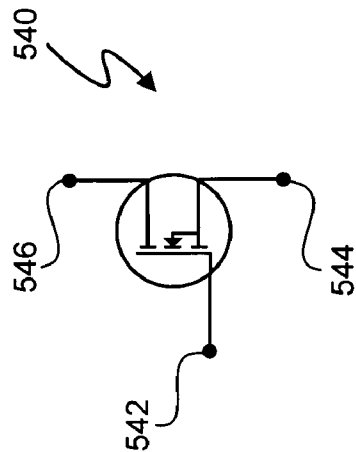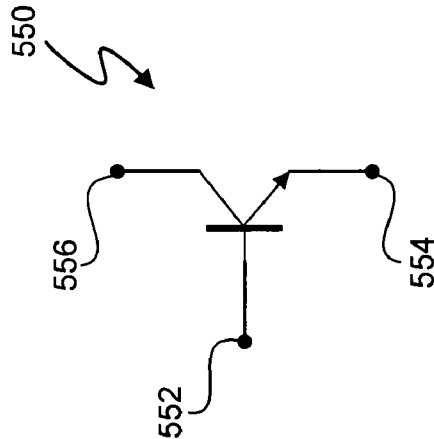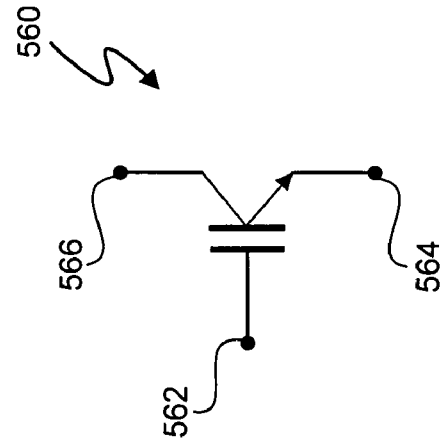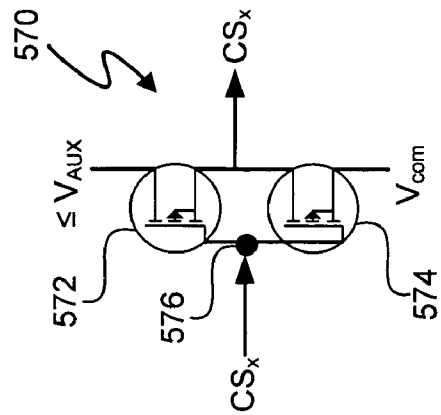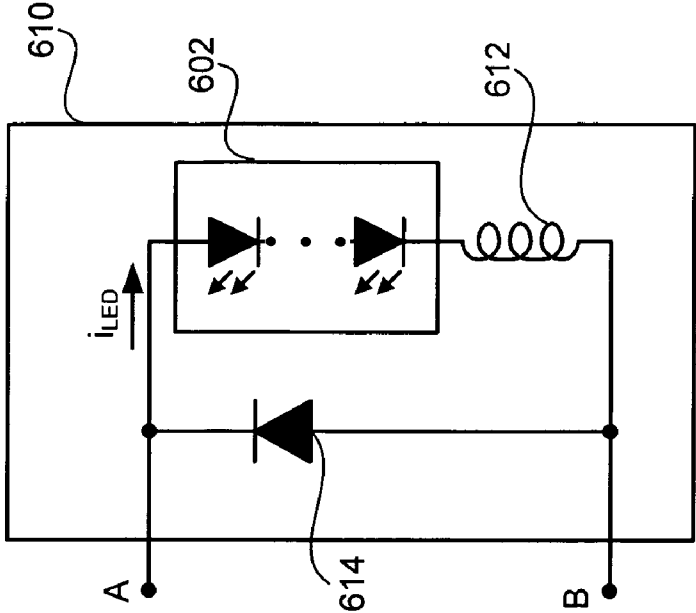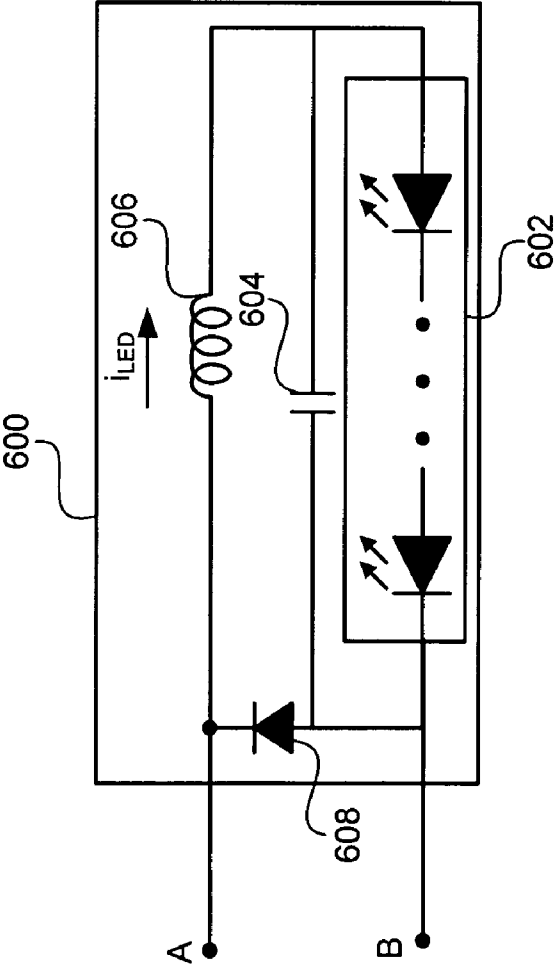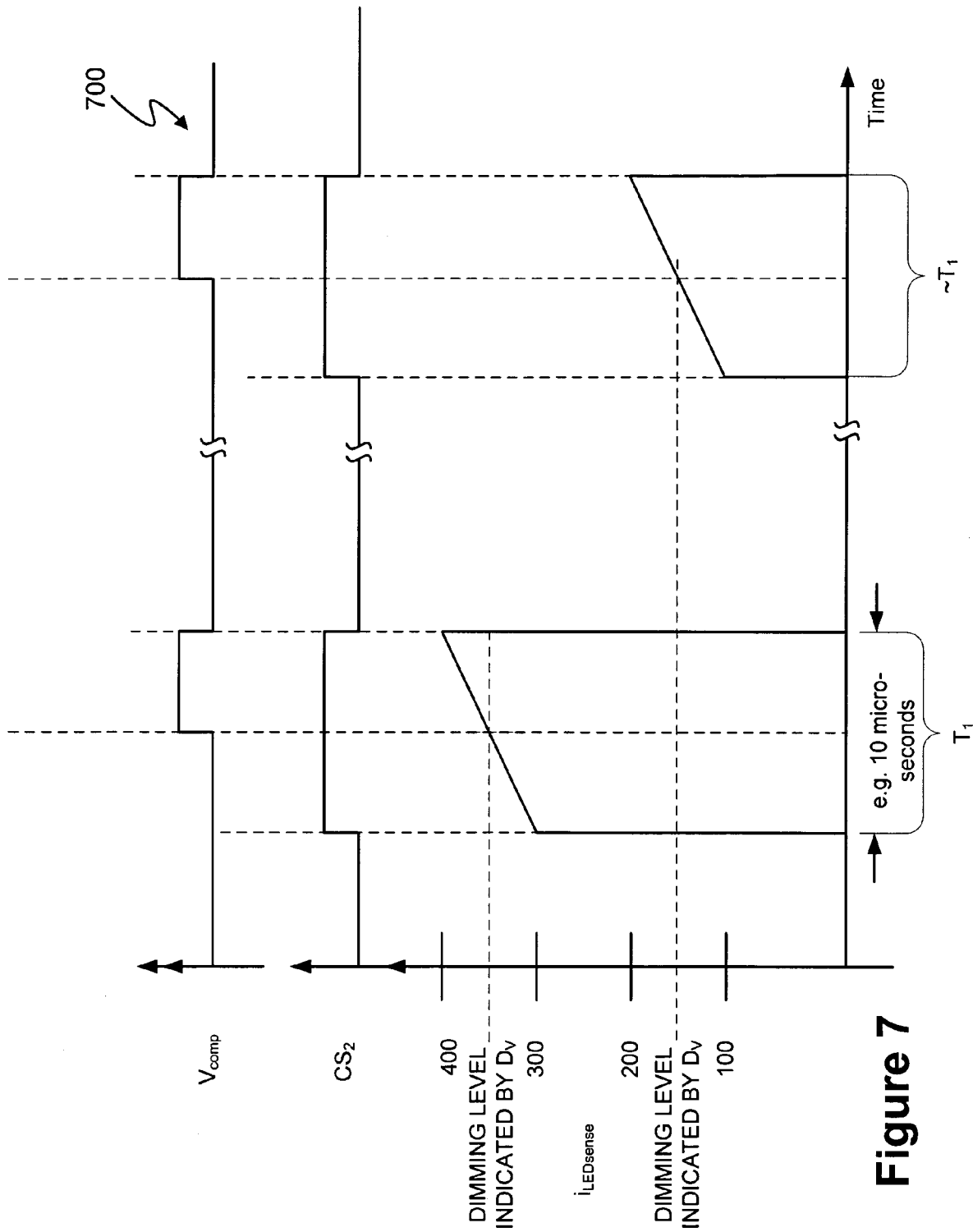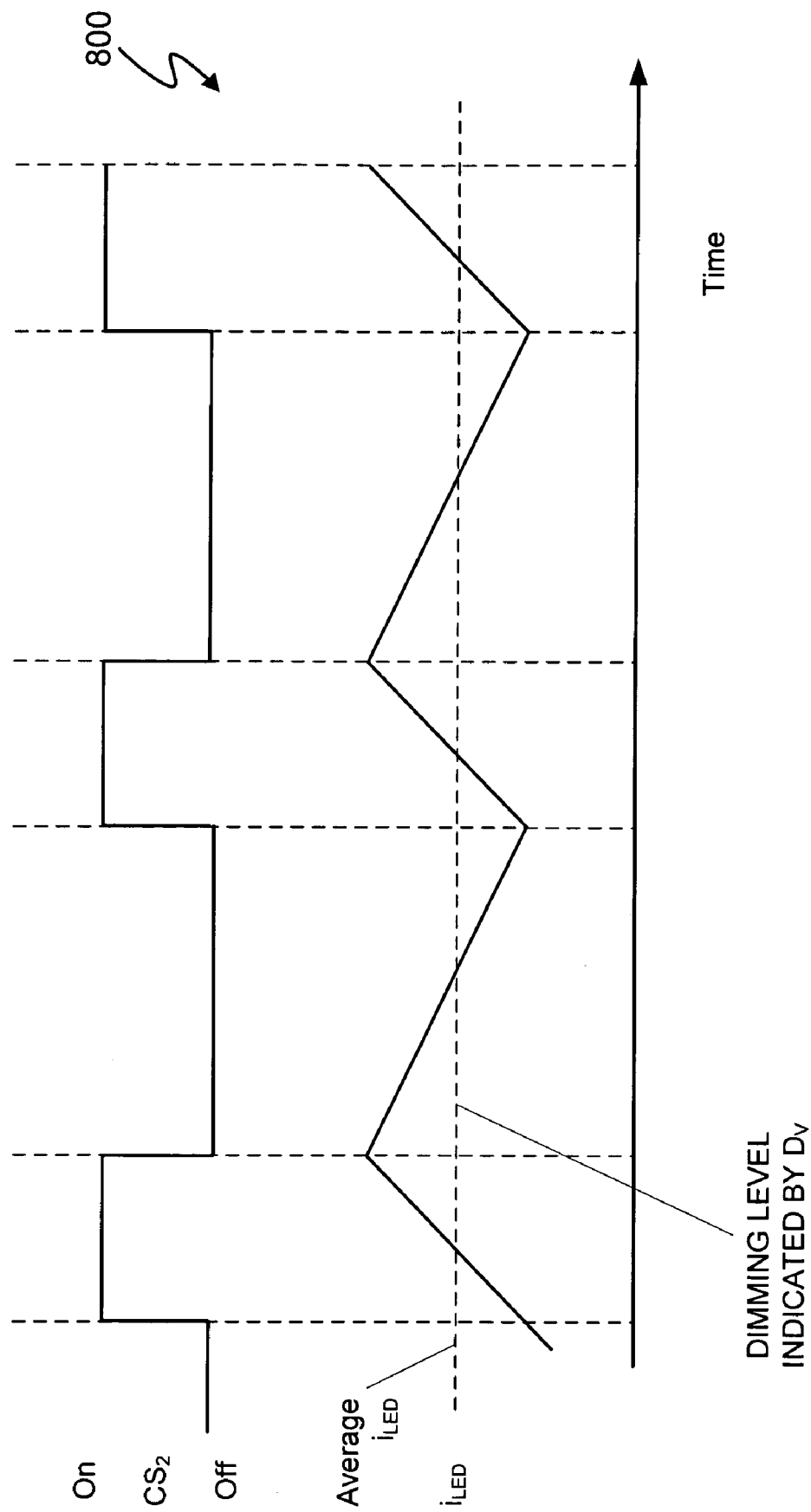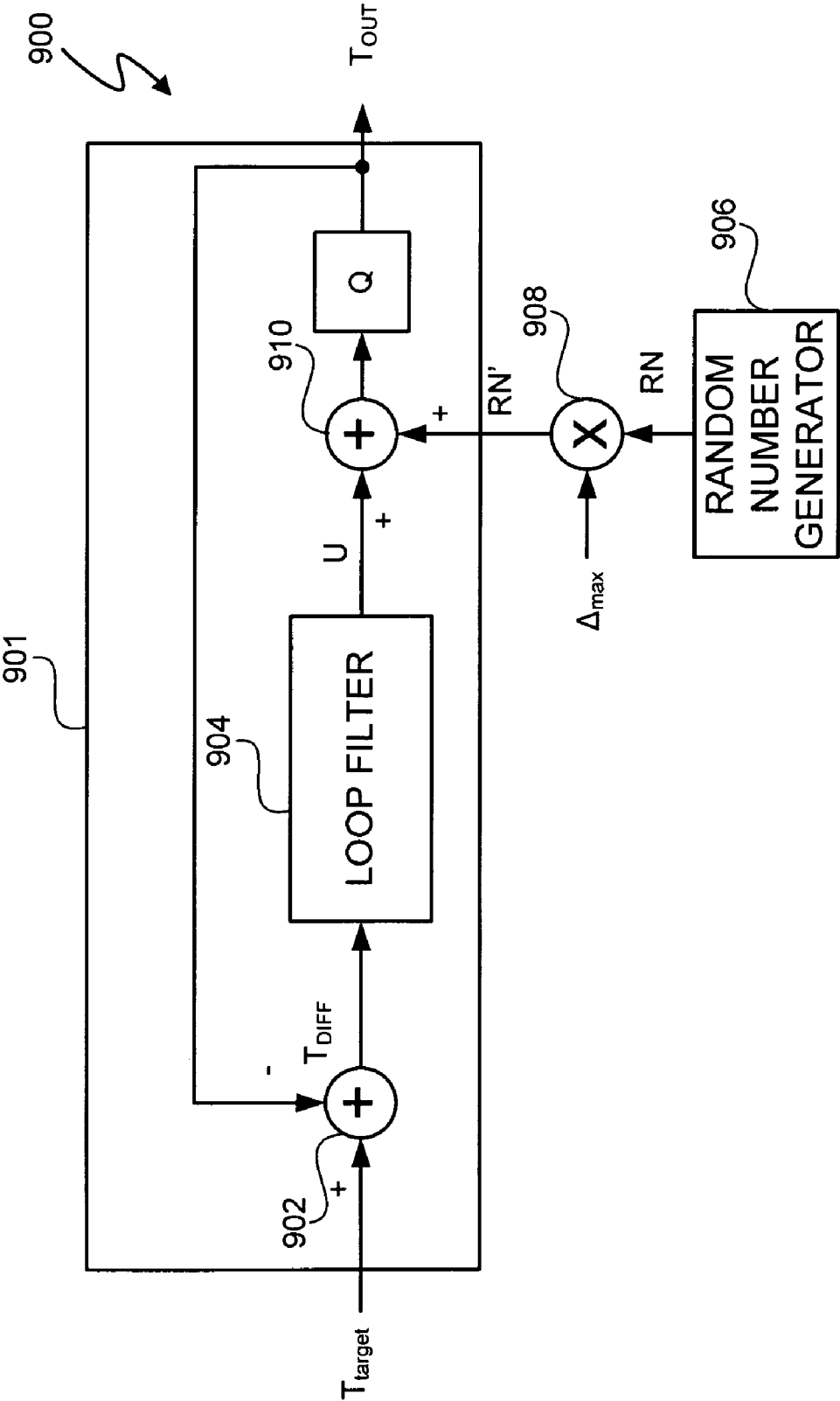
Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

1200

304.N

SWITCHING LED SYSTEM

$i_{LED.N}$

CS_{2B}
1204.N

$i_{LEDsense.N}$

304.0

SWITCHING LED SYSTEM

$i_{LED.0}$

V_{C1}
1204.0

CS_{2A}
1206

$i_{LEDsense.0}$

314.0

LEDisense

REF

438

V_{COMP}

DIMMER SIGNAL D_V

CONTROLLER

1208

i_{LED} CURRENT DETECTOR
1210

CS_1

$CS_{2.0}$

$CS_{2.N}$
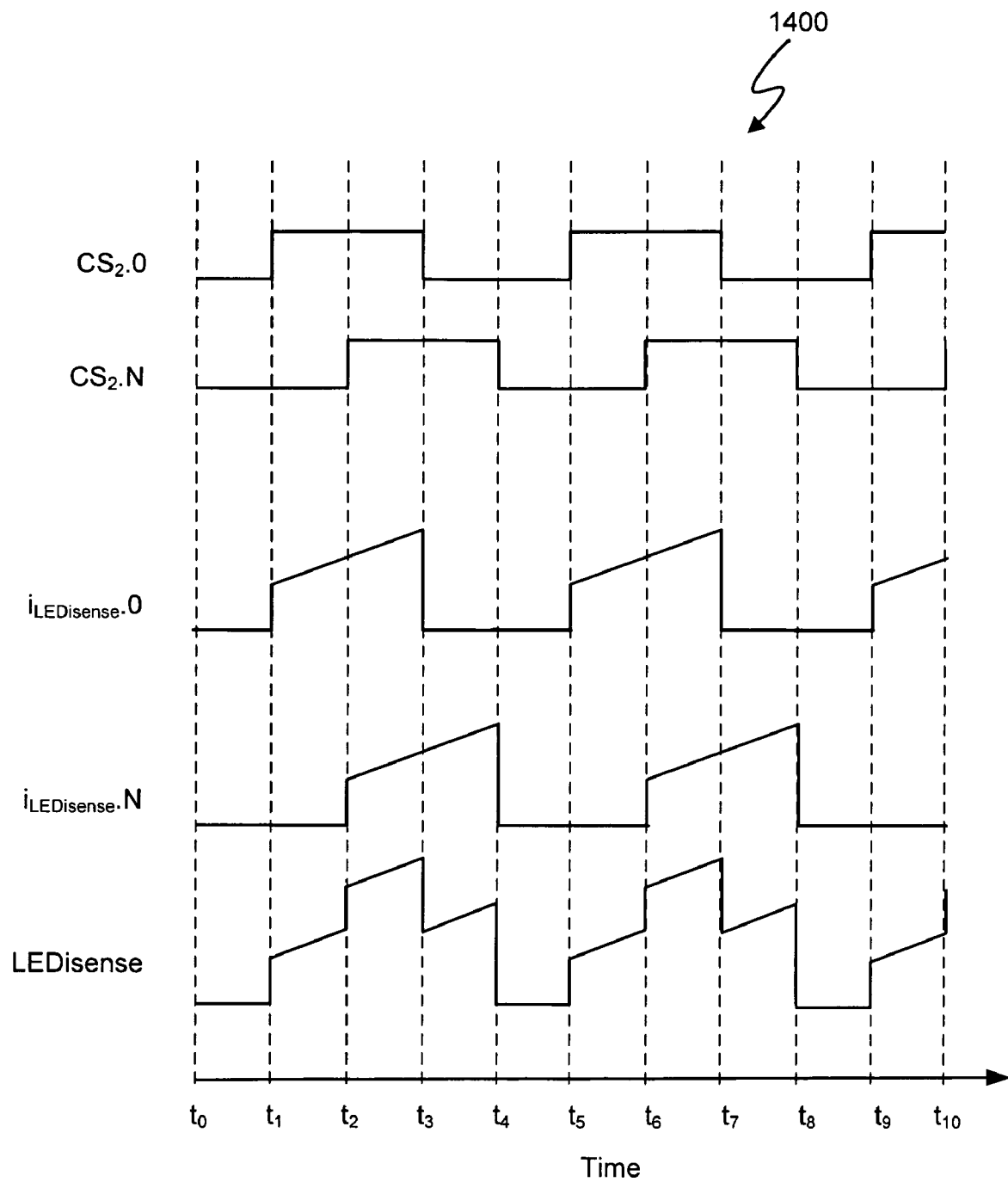
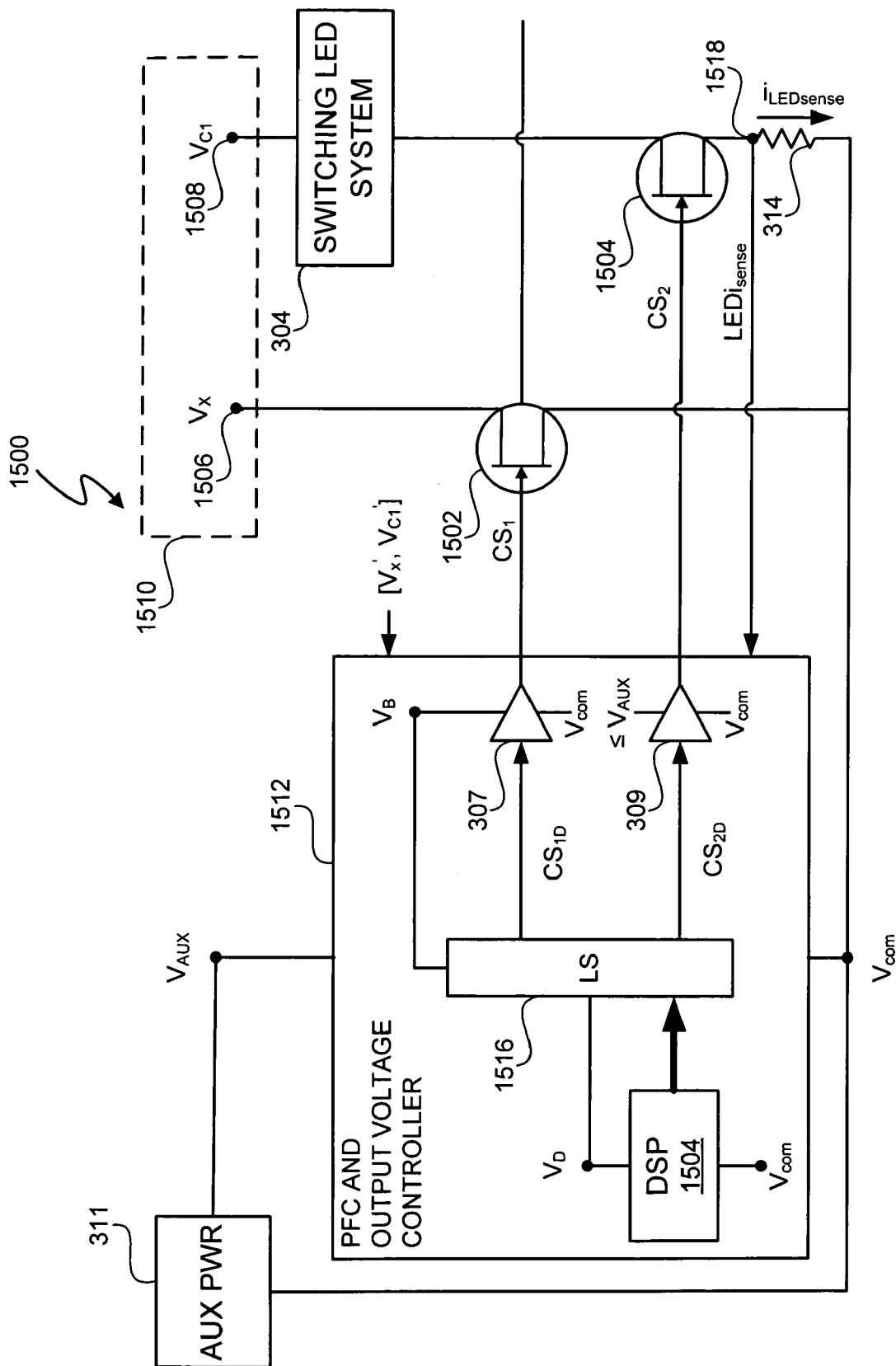**Figure 12**

1300
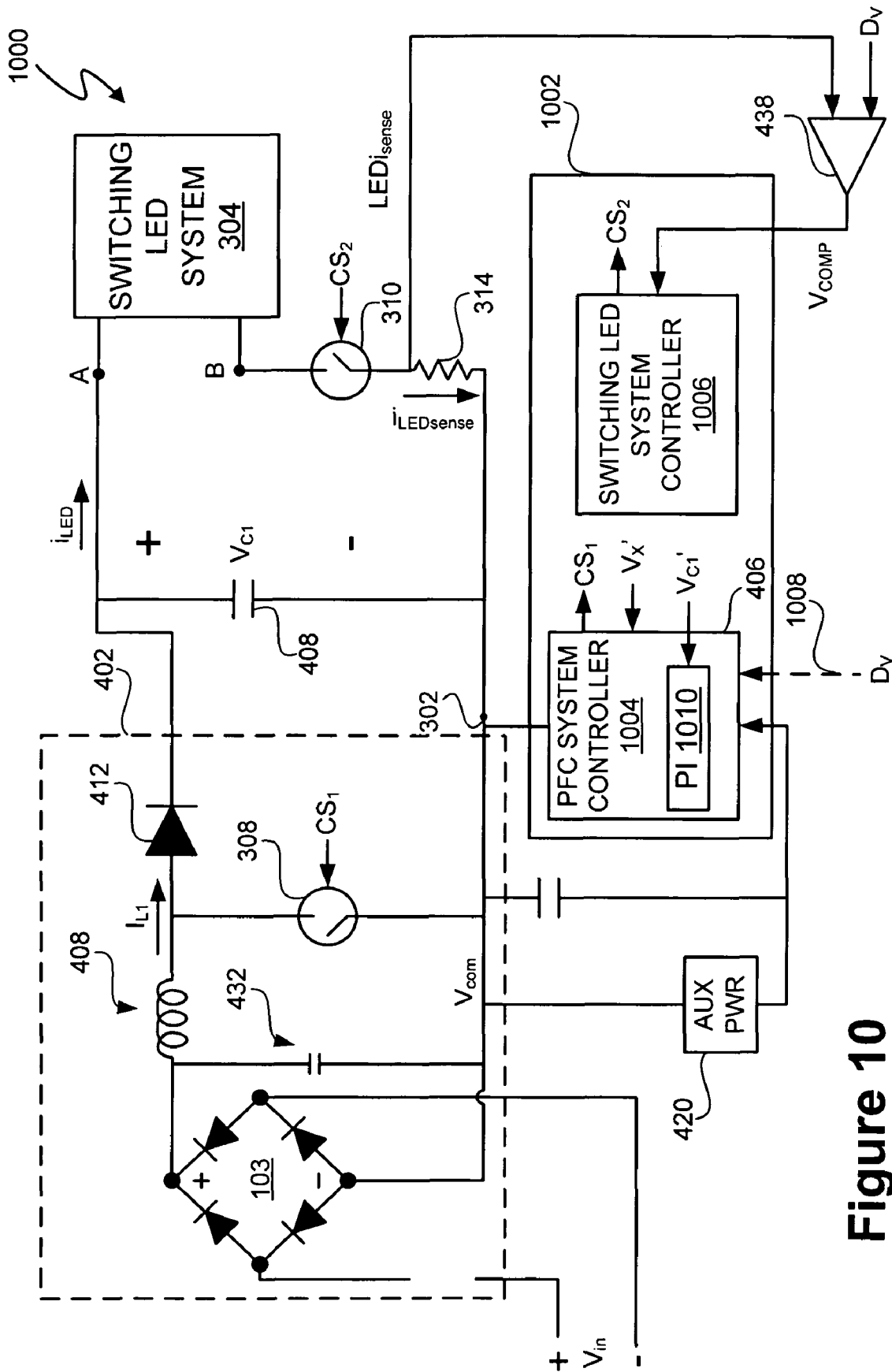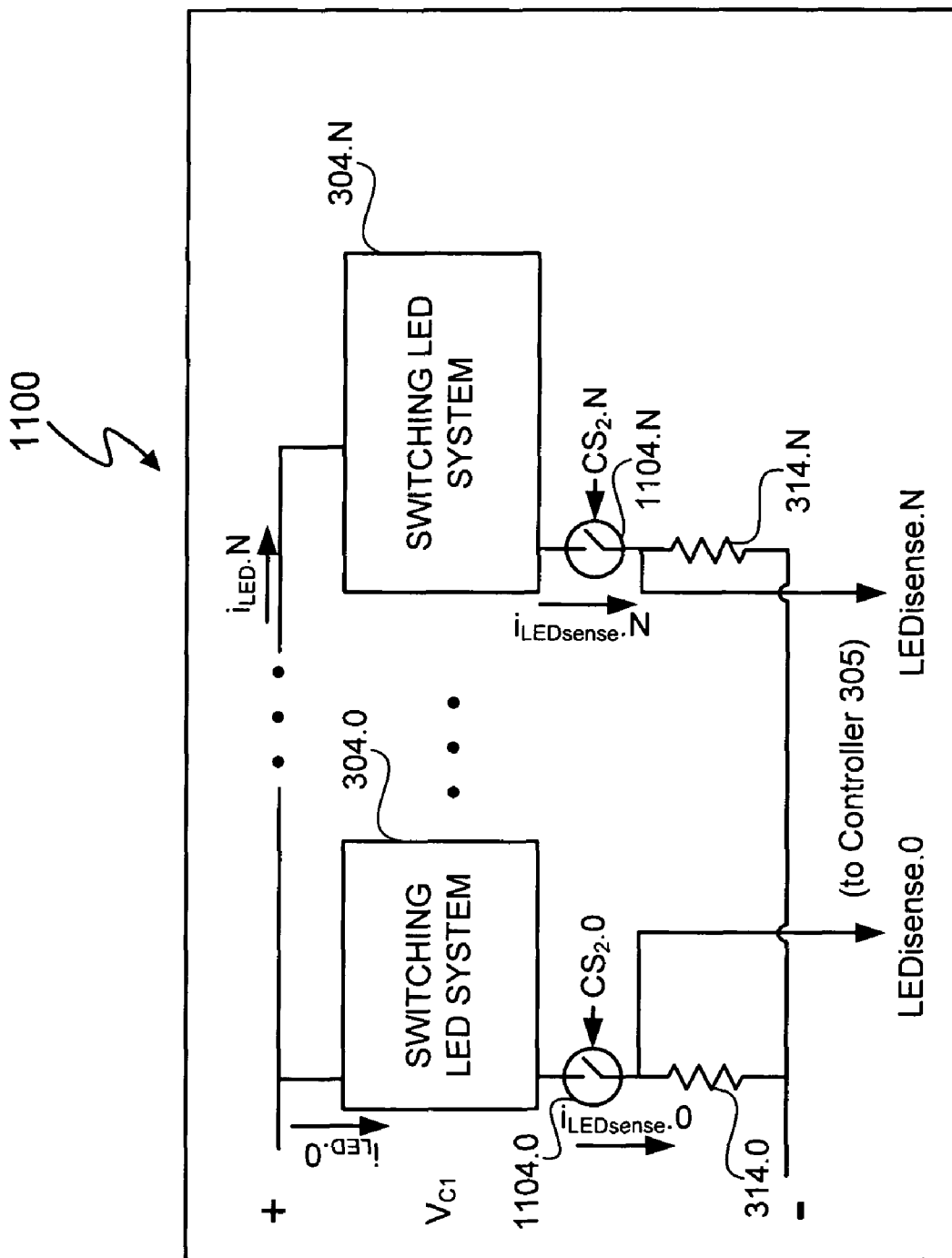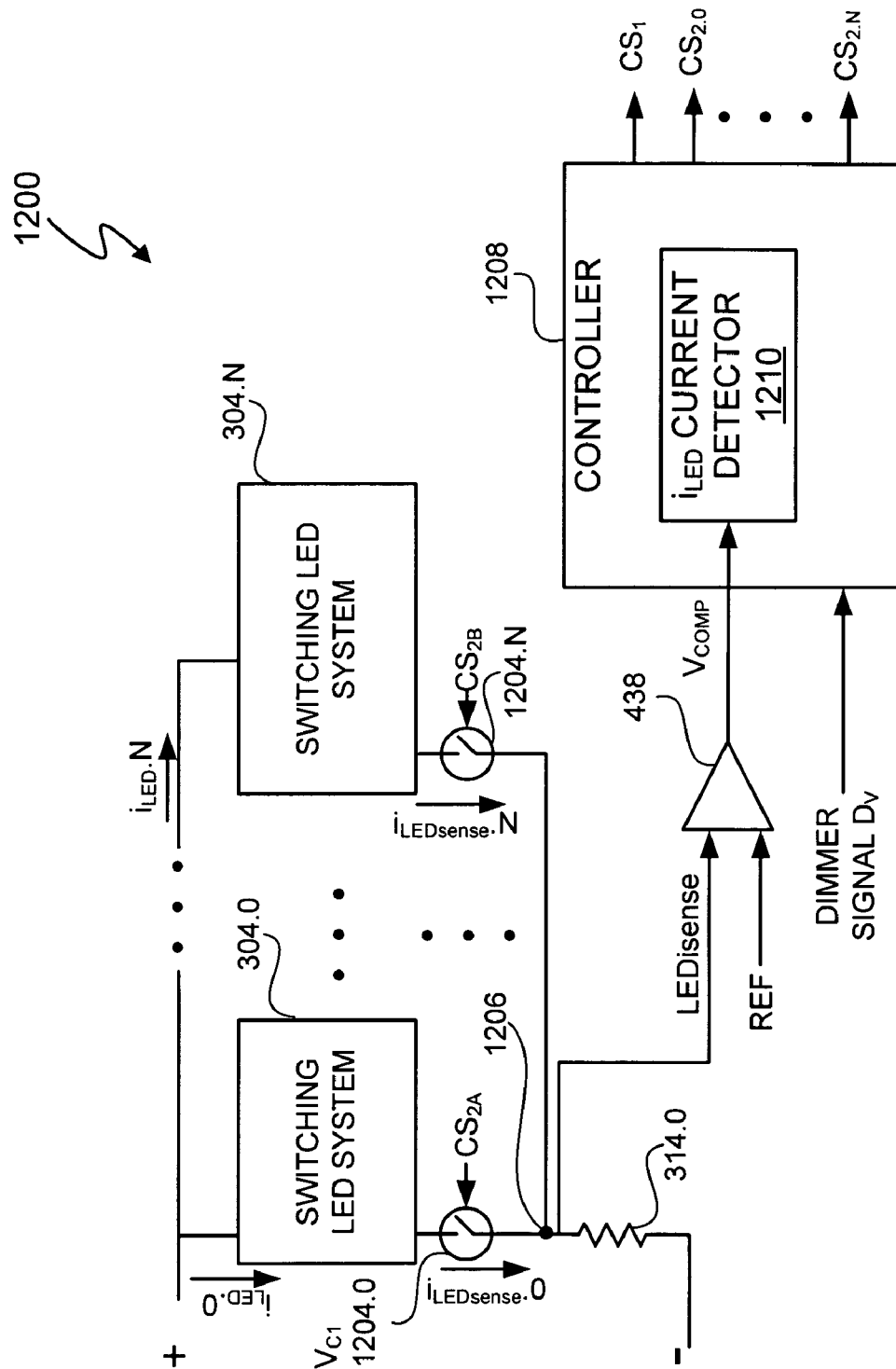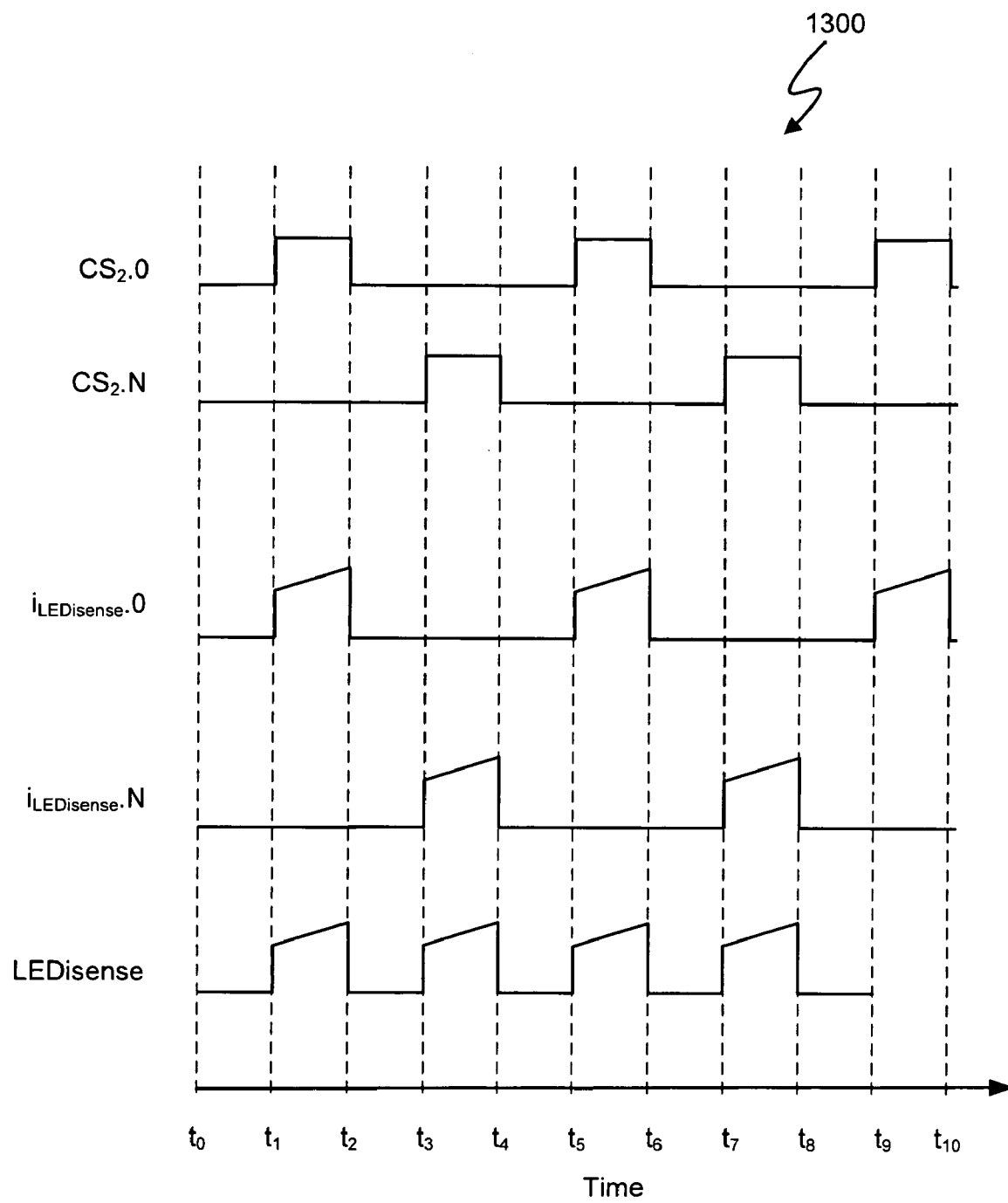
Figure 13

Figure 14

Figure 15

POWER CONTROL SYSTEM FOR CURRENT REGULATED LIGHT SOURCES

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. §119 (e) and 37 C.F.R. §1.78 of U.S. Provisional Application No. 60/894,295, filed Mar. 12, 2007 and entitled "Lighting Fixture." U.S. Provisional Application No. 60/894,295 includes exemplary systems and methods and is incorporated by reference in its entirety.

U.S. Provisional Application No. 60/909,458, entitled "Ballast for Light Emitting Diode Light Sources," inventor John L. Melanson, and filed on Apr. 1, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety.

U.S. patent application Ser. No. 12/047249, entitled "Ballast for Light Emitting Diode Light Sources," inventor John L. Melanson, and filed on Mar. 12, 2008 describes exemplary methods and systems and is incorporated by reference in its entirety.

U.S. patent application Ser. No. 11/926,864, entitled "Color Variations in a Dimmable Lighting Device with Stable Color Temperature Light Sources," inventor John L. Melanson, and filed on Mar. 31, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety.

U.S. Provisional Application No. 60/909,457, entitled "Multi-Function Duty Cycle Modifier," inventors John L. Melanson and John Paulos, and filed on Mar. 31, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson I.

U.S. patent application Ser. No. 12/047258, entitled "Multi-Function Duty Cycle Modifier," inventors John L. Melanson and John Paulos, and filed on Mar. 12, 2008 describes exemplary methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson II.

U.S. patent application Ser. No. 11/695,024, entitled "Lighting System with Lighting Dimmer Output Mapping," inventors John L. Melanson and John Paulos, and filed on Mar. 31, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety.

U.S. patent application Ser. No. 11/864,366, entitled "Time-Based Control of a System having Integration Response," inventor John L. Melanson, and filed on Sep. 28, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson III.

U.S. patent application Ser. No. 11/967,269, entitled "Power Control System Using a Nonlinear Delta-Sigma Modulator with Nonlinear Power Conversion Process Modeling," inventor John L. Melanson, and filed on Dec. 31, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson IV.

U.S. patent application Ser. No. 11/967,271, entitled "Power Factor Correction Controller with Feedback Reduction," inventor John L. Melanson, and filed on Dec. 31, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson V.

U.S. patent application Ser. No. 11/967,273, entitled "System and Method with Inductor Flyback Detection Using Switch Date Charge Characteristic Detection," inventor John L. Melanson, and filed on Dec. 31, 2007 describes exemplary

methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson VI.

U.S. patent application Ser. No. 11/967,275, entitled "Programmable Power Control System," inventor John L. Melanson, and filed on Dec. 31, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson VII.

U.S. patent application Ser. No. 11/967,272, entitled "Power Factor Correction Controller With Switch Node Feedback", inventor John L. Melanson, and filed on Dec. 31, 2007 describes exemplary methods and systems and is incorporated by reference in its entirety. Referred to herein as Melanson VIII.

U.S. patent application Ser. No. 12/047269, entitled "Lighting System with Power Factor Correction Control Data Determined from a Phase Modulated Signal," inventor John L. Melanson, and filed on Mar. 12, 2008 describes exemplary methods and systems and is incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates in general to the field of electronics and lighting, and more specifically to a system and method to controlling and/or providing power to current regulated light sources, such as light emitting diode light sources.

2. Description of the Related Art

Commercially practical incandescent light bulbs have been available for over 100 years. However, other light sources show promise as commercially viable alternatives to the incandescent light bulb. LEDs are becoming particularly attractive as main stream light sources in part because of energy savings through high efficiency light output, long life, and environmental incentives such as the reduction of mercury.

LEDs are semiconductor devices and are driven by direct current. The brightness of the LED varies in direct proportion to the current flowing through the LED. Thus, increasing current supplied to an LED increases the brightness of the LED and decreasing current supplied to the LED dims the LED.

FIG. 1 depicts a switching light emitting diode (LED) driver system 100. The LED driver system 100 includes a continuous current mode, buck-based power converter 102 to provide a constant mains voltage V_{mains} to switching LED system 104. Voltage source 101 supplies an alternating current (AC) input mains voltage V_{mains} to a full, diode bridge rectifier 103. The voltage source 101 is, for example, a public utility, and the AC mains voltage V_{mains} is, for example, a 60 Hz/120 V mains voltage in the United States of America or a 50 Hz/230 V mains voltage in Europe. The rectifier 103 rectifies the input mains voltage V_{mains}. The hold-up capacitor C1 holds an approximately direct current (DC) supply voltage V_{C1} across capacitor C1 relative to a reference voltage V_R. Supply voltage V_{C1} is also the output voltage of power converter 102 and the input voltage for controller 106. Input filter capacitor C2 provides a high pass filter for high frequency components of the output voltage of rectifier 103. A thermistor NTC 1 provides in-rush current protection for power converter 102.

The controller 106 is, for example, a Supertex HV9910B integrated circuit controller available from Supertex, Inc. of Sunnyvale, Calif. The supply voltage V_{C1} can vary from, for example, 8V to 450V. Controller 106 incorporates an internal voltage regulator to operate directly from the DC supply voltage V_C. The controller 106 provides a gate drive signal

from the GATE output node to the n-channel metal oxide semiconductor field effect transistor (MOSFET) Q1. Controller **106** modulates the gate drive signal and, thus, the conductivity of MOSFET Q1 to provide a constant current to switching LED system **104**. Controller **106** modifies the average resistance of MOSFET Q1 by varying a duty cycle of a pulse width modulated gate drive signal V_{GATE}. Resistor R_1 and capacitor C_3 provide external connections for controller **106** to the ground reference.

Controller **106** generates and uses feedback to maintain a constant current i_{LED}. Controller **106** receives a current feedback signal V_{fb} representing a feedback voltage V_{fb} sensed across sense resistor R_2. The feedback voltage V_{fb} is directly proportional to the LED current i_{LED} in LEDs **108**. If the feedback voltage V_{fb} exceeds a predetermined reference corresponding to a desired LED current, the controller **106** responds to the feedback voltage V_{fb} by decreasing the duty cycle of gate drive signal GATE to increase the average resistance of MOSFET Q1 over time. If the feedback voltage V_{fb} is less than a predetermined reference corresponding to the desired LED current, the controller **106** responds to the feedback voltage V_{fb} by increasing the duty cycle of gate drive signal V_{GATE} to decrease the average resistance of MOSFET Q1 over time.

The switching LED system **104** includes a chain of one or more, serially connected LEDs **108**. When the MOSFET Q1 is "on", i.e. conductive, diode D1 is reversed bias and, current i_{LED} flows through the LEDs and charges inductor L_1. When the MOSFET Q1 is "off", i.e. nonconductive, the voltage across inductor L_1 changes polarity, and diode D1 creates a current path for the LED current i_{LED}. The inductor L_1 is chosen so as to store enough energy to maintain a constant current i_{LED} when MOSFET Q1 is "off".

FIG. 2 depicts a power control system **200**, which includes a switching power converter **202**. The rectifier **103** rectifies the input mains voltage V_{mains} and supplies a rectified, time-varying, primary supply voltage V_x to the switching power converter. The switching power converter **202** provides a power factor corrected, approximately constant voltage power to load **222**.

PFC and output voltage controller **214** controls PFC switch **208** so as to provide power factor correction and regulate the output voltage V_c of switching power converter **202**. The goal of power factor correction technology is to make the switching power converter **202** appear resistive to the voltage source **101**. Thus, the PFC and output voltage controller **214** attempts to control the inductor current i_L so that the average inductor current i_L is linearly and directly related to the primary supply voltage V_x. The PFC and output voltage controller **214** supplies a pulse width modulated (PWM) control signal CS_0 to control the conductivity of switch **208**. In at least one embodiment, switch **208** is a field effect transistor (FET), and control signal CS_0 is the gate voltage of switch **208**. The values of the pulse width and duty cycle of control signal CS_0 depend on two feedback signals, namely, the primary supply voltage V_x and the capacitor voltage/output voltage V_c. Output voltage V_c is also commonly referred to as a "link voltage".

To convert the input voltage V_x into a power factor corrected output voltage V_c, PFC and output voltage controller **214** modulates the conductivity of PFC switch **208**. To regulate the amount of energy transferred and maintain a power factor close to one, PFC and output voltage controller **214** varies the period of control signal CS_0 so that the input current i_L tracks the changes in input voltage V_x and holds the output voltage V_C constant. Thus, as the input voltage V_x increases, PFC and output voltage controller **214** increases the period

TT of control signal CS_0, and as the input voltage V_x decreases, PFC and output voltage controller **214** decreases the period of control signal CS_0. At the same time, the pulse width (PW) of control signal CS_0 is adjusted to maintain a constant duty cycle of control signal CS_0, and, thus, hold the output voltage V_C constant. The inductor current i_L ramps 'up' when the switch **208** conducts, i.e. is "ON". The inductor current i_L ramps down when switch **208** is nonconductive, i.e. is "OFF", and supplies inductor current i_L to recharge capacitor **206**. The time period during which inductor current i_L ramps down is commonly referred to as the "inductor flyback time". Diode **211** prevents reverse current flow into inductor **210**. Inductor current i_L is proportionate to the 'on-time' of switch **208**. In at least one embodiment, the switching power converter **202** operates in discontinuous current mode, i.e. the inductor current i_L ramp up time plus the inductor flyback time is less than the period of the control signal CS_0, which controls the conductivity of switch **208**. Prodić, *Compensator Design and Stability Assessment for Fast Voltage Loops of Power Factor Correction Rectifiers*, IEEE Transactions on Power Electronics, Vol. 22, No. 5, September 2007, pp. 1719-1729 (referred to herein as "Prodić"), describes an example of PFC and output voltage controller **214**.

In at least one embodiment, the PFC and output voltage controller **214** updates the control signal CS_0 at a frequency much greater than the frequency of input voltage V_x. The frequency of input voltage V_x is generally 50-60 Hz. The frequency 1/TT of control signal CS_0 is, for example, between 20 kHz and 130 kHz. Frequencies at or above 20 kHz avoid audio frequencies and frequencies at or below 130 kHz avoids significant switching inefficiencies while still maintaining a good power factor of, for example between 0.9 and 1, and an approximately constant output voltage V_C.

Capacitor **206** supplies stored energy to load **212** when diode **211** is reverse biased. The capacitor **206** is sufficiently large so as to maintain a substantially constant output voltage V_c, as established by a PFC and output voltage controller **214** (as discussed in more detail below). The output voltage V_c remains at a substantially constant target value during constant load conditions. However, as load conditions change, the output voltage V_c changes. The PFC and output voltage controller **214** responds to the changes in voltage V_c by adjusting the control signal CS_0 to return the output voltage V_c to the target value. The PFC and output voltage controller **214** includes a small capacitor **215** to filter any high frequency signals from the primary supply voltage V_x.

PFC and output voltage controller **214** controls the process of switching power converter **202** so that a desired amount of energy is transferred to capacitor **206**. The desired amount of energy depends upon the voltage and current requirements of load **212**. To determine the amount of energy demand of load **212**, the PFC and output voltage controller **214** includes a compensator **228**. Compensator **228** determines a difference between a reference voltage VREF, which indicates a target voltage for output voltage V_c, and the actual output voltage V_c sensed from node **222** and received as feedback from voltage loop **218**. The compensator **228** generally utilizes technology, such as proportional integral (PI) type control, to respond to differences in the output voltage V_c relative to the reference voltage V_{REF}. The PI control processes the error so that the PFC and output voltage controller **214** smoothly adjusts the output voltage V_c to avoid causing rapid fluctuations in the output voltage V_c in response to small error signals. The compensator **228** provides an output signal to the pulse width modulator (PWM) **230** to cause the PWM **230** to generate a control signal CS_0 that drives switch **208**.

An LED lighting system controller, such as controller **106**, using a supply voltage that can vary from, for example, 8V to 450V generally requires a more expensive integrated circuit relative to an integrated circuit designed to operate at a fraction of the maximum supply voltage. Using a conventional PFC controller with feedback control, when the power demand of a load quickly decreases, the output voltage V_C will momentarily increase while the PFC controller responds to output voltage feedback by lowering the output voltage. Conventional switching power converters using compensators generally respond relatively slowly to large changes in load power demand. Additionally, conventional PFC controllers often include large and relatively expensive electrolytic capacitors to accommodate voltage spikes.

SUMMARY OF THE INVENTION

In one embodiment of the present invention, a light emitting diode (LED) lighting system includes a power factor correction (PFC) and LED drive controller. The controller includes a digital signal processor, coupled to the LED feedback node and configured to: operate from a digital level supply voltage; generate a PFC control signal; and generate an LED current control signal. The controller further includes a first buffer, coupled to the processor, and configured to: operate from a medium level supply voltage. The medium level supply voltage is greater than the digital level supply voltage. The controller is further configured to receive the PFC control signal and convert the PFC control signal into a PFC switch control signal to control conductivity of a high voltage PFC switch. The controller further includes a second buffer, coupled to the processor, and configured to: operate from the medium level supply voltage; receive the LED current control signal; and convert the LED current control signal into an LED current control switch signal to control conductivity of a high voltage LED current control switch.

In another embodiment of the present invention, a method includes operating a digital signal processor of a power factor correction (PFC) and output voltage controller from a digital level supply voltage and generating a PFC control signal; and generating an LED current control signal. The method further includes operating a first buffer, coupled to the processor, from a medium level supply voltage. The medium level supply voltage is greater than the digital level supply voltage; receiving the PFC control signal. The method also includes converting the PFC control signal into a PFC switch control signal to control conductivity of a high voltage PFC switch and operating a second buffer, coupled to the processor, from the medium level supply voltage. The method further includes receiving the LED current control signal and converting the LED current control signal into an LED current control switch signal to control conductivity of a high voltage LED current control switch.

In a further embodiment of the present invention, a light emitting diode (LED) lighting system includes an LED lighting power system. During normal operation of the LED lighting system the LED lighting power system generates a first source voltage relative to a common voltage. The first source voltage is a link voltage. The LED lighting power system includes a switching power supply having a power factor correction (PFC) switch, wherein during normal operation of the LED lighting system, the PFC switch of the LED lighting power system operates at a current node voltage less than or equal to 0.1 times the first source voltage relative to the common voltage reference. The LED lighting power system also includes an LED current control switch, wherein during normal operation of the LED lighting system, the LED cur-

rent control switch operates at a current node voltage less than or equal to 0.1 times the first source voltage relative to the common voltage reference. The LED lighting system further includes a PFC and output voltage controller coupled to conductivity control nodes of the first and LED drive current switches. During normal operation of the lighting control system, the controller operates from a second source voltage relative to the common voltage and controls conductivity of the PFC switch and the LED current control; and at least one LED coupled to the LED current control switch.

BRIEF DESCRIPTION OF THE DRAWINGS

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.

FIG. **1** (labeled prior art) depicts a switching light emitting diode (LED) driver system

FIG. **2** (labeled prior art) depicts a power control system, which includes a switching power converter.

FIG. **3** depicts a LED lighting system that includes a common reference node at a common reference voltage.

FIG. **4** depicts a LED lighting system.

FIGS. **5A**, **5B**, **5C**, and **5D** depict various switches.

FIG. **5E** depicts a driver circuit.

FIGS. **6A** and **6B** depict switching LED systems.

FIGS. **7-8** depict graphical relationships between various control signals, sense signals, and currents of the LED lighting system of FIG. **4**.

FIG. **9** depicts a spread spectrum system.

FIG. **10** depicts one embodiment of a feed forward lighting power and control system.

FIG. **11** depicts a switching LED system with multiple current sense elements.

FIG. **12** depicts a switching LED system with a single current sense element.

FIG. **13** depicts a graphical representation of non-overlapping control signals and current sense signals.

FIG. **14** depicts a graphical representation of overlapping control signals and current sense signals.

FIG. **15** depicts an embodiment of a controller of the lighting system of FIG. **3**.

DETAILED DESCRIPTION

A light emitting diode (LED) lighting system includes a PFC and output voltage controller and a LED lighting power system. The LED lighting power system operates from a primary supply voltage derived from a primary power supply. The controller operates from an auxiliary power source supply, which provides an auxiliary voltage less than a link voltage generated by the LED lighting power system relative to a common reference voltage at a common reference node. By utilizing a lower voltage, in at least one embodiment, the controller can be manufactured at a lower cost than a comparable controller supplied by the primary power supply utilized by the LED lighting power system. Additionally, during normal operation of the LED lighting system, a power factor correction (PFC) switch and an LED drive current switch of the LED lighting system, that respectively control power factor correction and LED drive current, are coupled to the common reference node and have control node-to-common node, absolute voltage that allows the controller to control the conductivity of the switches. In at least one embodiment, the PFC switch and the LED drive current switch each have a

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control node-to-common node, absolute voltage within 15% of the link voltage relative to the common reference voltage. Having a current node voltage within 15% of the absolute value of the link voltage relative to the common reference voltage allows the controller to effectively control the switches.

In at least one embodiment, the controller 305 is manufactured in a 12-20 Volt ("V") complimentary metal oxide semiconductor (CMOS) integrated circuit process ("IC Process"), coupled to 200V-500V rated field effect transistors (FETs) external to the integrated circuit (IC) controller. This embodiment is a particularly cost-effective combination of technologies. In a further refinement of the preferred embodiment, the IC Process also includes 5V or lower transistors in the IC controller in addition to the 12V-20V transistors, allowing for dense digital designs. A digital controller, in 0.35 micron or finer process technology allows for a very small, cost effective, digital controller. A 12V-20V process allows for the appropriate driving of the gates of external high-voltage FETs. In at least one embodiment, the IC controller is controller 305 (FIGS. 3 and 4). The foregoing voltage limits typically indicate that the high voltage devices (which have approximately 12V of gate-source voltage to be fully turned on, and less than 1V to be fully turned off) have sources at nearly the same voltage potential, in order that the same controller can drive both.

An LED lighting system that includes dimming capability can be subject to rapid changes in power demand by a switching LED system load. The switching LED system includes one or more light emitting diodes (LED(s)). For example, if the LED(S) are operating at full intensity and a dimming level of 15% of full intensity is requested, the power demand of the switching LED system is quickly and significantly reduced. In at least one embodiment, the LED lighting system utilizes feedforward control to allow the controller to concurrently modify power demand by the LED lighting power system and power demand of one or more switching LED systems. Thus, in at least one embodiment, the LED lighting system can quickly respond to the lower power demand by reducing power received from a power source, such as a mains source, and use a compensator, such as a proportional integral (PI) type control, to make relatively small corrections to maintain a desired LED lighting system output voltage.

Additionally, in at least one embodiment, the LED lighting system includes multiple switching LED systems, and each switching LED system includes at least one LED. In at least one embodiment, the LED lighting system utilizes a common current sense device to provide a common feedback signal to the controller representing current in at least two of the switching LED systems. In at least one embodiment, utilizing a common current sense device reduces a number of pins of the controller used for feedback and reduces a number of current sense devices.

FIG. 3 depicts a LED lighting system 300 that includes a common reference node 302 at a common reference voltage V_{com}, such as a ground reference during normal operation. The LED lighting system 300 operates from two supply voltages, V_X and V_{AUX}, which are both referenced to the common reference voltage. A third voltage, V_D (shown in FIG. 15), can be generated internal to the controller 305 and is preferably in the range of 1.5V-5.0V, depending on the chosen CMOS technology. "Normal operation" refers to the operation of LED lighting system 300 after power has been supplied to the LED lighting system 300 and any initial voltage or current transients have subsided. The LED lighting system 300 generates a link voltage V_{C1}. The PFC switch 308 and LED drive current control switch 310 have absolute, control node-to-

common node voltages within 15% of the difference between the absolute link voltage V_{C1} minus the common reference voltage V_{com}, ie. $V_{C1}-V_{com}$. PFC and output voltage controller 305 (referred to as "controller 305") operates from an auxiliary supply voltage V_{AUX}. The absolute value of auxiliary supply voltage V_{AUX} is less than the absolute value of the link voltage V_{C1}.

FIGS. 5A, 5B, 5C, and 5D depict exemplary embodiments of switch 530, which represents one embodiment of switches 308 and 310. Referring to FIG. 5A, the nodes of 532, 534, and 536 of generic switch 530 represent respective control, common, and switching nodes. FIGS. 5B, 5C, and 5D represent embodiments of switch 530. Referring to FIG. 5B, switch 540 is an n-channel MOSFET, and gate node 542, source node 544, and drain node 546 respectively represent a control node, a common node, and a switching node. Referring to FIG. 5C, switch 550 is a bipolar junction transistor (BJT), and base node 552, emitter node 554, and collector 556 respectively represent a control node, a common node, and a switching node. Referring to FIG. 5D, switch 560 is an insulated gate bipolar transistor (IGBT), and gate node 562, emitter node 564, and collector 566 respectively represent a control node, a common node, and a switching node.

FIG. 5E depicts an exemplary driver circuit 570, which represents one embodiment of drivers 307 and 309. The source of p-channel FET 572 and the drain of n-channel FET 574 are connected together and provide the output signal CSX where CSX represents control signals CS_1 and CS_2. The drain of p-channel FET 572 is connected to the high side supply rail voltage, which is less than or equal to auxiliary voltage V_{AUX}. The source of n-channel FET 574 is connected to the low side supply rail voltage V_{com}. FETs 572 and 574 share a gate node 576 to receive the control signal CS_x.

Referring to FIG. 3, diode rectifier 103 rectifies the input mains voltage V_{mains} and supplies a rectified, time-varying, primary supply voltage V_x to a switching power converter 303. In at least one embodiment, mains voltage V_{mains} a mains voltage such as the mains voltage V_{mains} in FIGS. 1 and 2. Referring to FIG. 3, the auxiliary power supply 311 provides low voltage power to the controller 305. Providing low voltage power to the controller 305 allows controller 305 to be manufactured at a lower cost than higher voltage controllers. Additionally, during normal operation of the LED lighting system, a power factor correction (PFC) switch and an LED drive current switch of the LED lighting system, that respectively control power factor correction and LED drive current, are coupled to the common reference node and have control node-to-common node, absolute voltage that allows the controller to control the conductivity of the switches. During normal operation, the switching power converter 303 converts the primary supply voltage V_x into an output, link voltage V_{C1}. In at least one embodiment, by referencing controller 305 to the common reference node and establishing the control node-to-common node voltages of switches 308 and 310 within 15% of the voltage difference $V_{C1}-V_{com}$, controller 305 is able to control the conductivity of the switches 308 and 310 while operating from the auxiliary voltage V_{AUX} of auxiliary power supply 311. In at least one embodiment, the voltages at current nodes 312 and 313 are within +1V of the common reference voltage V_{com}. A current sense resistor may or may not be required in the PFC switch 308, depending on the control mode chosen for the controller 305. In the preferred embodiment, controller 305 is a discontinuous current mode controller and does not use a current sense for controlling power factor correction.

The auxiliary power supply 311 supplies power to controller 305. The auxiliary power supply 311 provides a supply

voltage V_{AUX} less than, such as approximately from 1% to 15%, the absolute value of the link voltage V_{C1}. For example, in at least one embodiment, the nominal RMS primary supply voltage V_x is 110V, and the supply voltage V_{AUX} is any value within the range of +1V to +15V, such as +1V, +3V, +5V, +12V, or +15V. Because controller 305 is powered by a relatively small supply voltage, controller 305 can be manufactured less expensively than a controller manufactured for higher supply voltages. The voltage V_{AUX} is chosen commensurate with the required drive voltage of the external switch. For an FET, this voltage is typically around 12V. For a bipolar transistor, current drive would often be used, and the voltage would be 1V-2V.

During normal operation, the switching power converter 303 converts the primary supply voltage V_x into an output, link voltage V_{C1}. In at least one embodiment, switching power converter 303 is a boost converter, i.e. link voltage $V_{C1} > V_x$. For a particular dimming level, the switching power converter 303 provides an approximately constant current i_{LED} to LED light source 308. The current i_{LED} varies with dimming levels but, in at least one embodiment, is approximately constant for a particular dimming level. The switching power converter 303 includes switch 308 to control the input current i_{in} so that the average input current i_{in} is linearly and directly related to the primary supply voltage V_x, thereby making the switching power converter 303 appear resistive to voltage source 301. By controlling the input current i_{in}, switch 308 also controls the value of link voltage V_{C1}. During normal operation of the LED lighting system 300, the link voltage V_{C1} has an approximately constant value over time and, thus, approximates a DC voltage. In at least one embodiment, the switching LED system 304 includes one or more individual LEDs or one or more parallel coupled strings of LED(s) as, for example, described in more detail with reference to FIGS. 5A and 5B. The link voltage V_{C1} is typically in the range of 200V-500V, depending on the AC mains voltage V_{mains}.

Controller 305 generates PFC control signal CS_1 to control the conductivity of switch 308. Controller 305 includes a buffer 307 to provide the drive current for PFC control signal CS_1. Controller 305 generates a digital PFC control signal CS_{1D} that is amplified by buffer 307 to generate PFC switch control signal CS_1. Buffer 307 operates from a high side voltage supply rail of less than or equal to auxiliary voltage V_{AUX} and from a low side voltage supply rail of common voltage V_{com}. Controller 305 adjusts the pulse width of PFC control signal CS_1 to increase as the primary supply voltage V_x increases and to decrease as primary supply voltage V_x decreases to provide power factor correction. Controller 305 maintains a duty cycle of PFC control signal CS_1 while adjusting the pulse width of PFC control signal CS_1 to maintain an approximately constant link voltage V_{C1}. Controller 305 receives feedback signal V_x' to detect the value of voltage V_x. Controller 305 also receives feedback signal V_{C1}' to detect the value of voltage V_{C1}. Controller 305 uses the value of detected feedback signals V_x' and V_{C1}' to adjust PFC control signal CS_1 so that switching power converter 303 provides power factor correction and maintains an approximately constant link voltage V_{C1}.

The controller 305 can be implemented to generate the PFC control signal CS_1 in any of a variety of ways, such as the exemplary ways described in Melanson IV, Melanson V, and Melanson VII. The feedback signals V_x' and V_{C1}' can be generated in any of a variety of ways, such as the exemplary ways described in Melanson V, Melanson VI, and Melanson VIII.

Controller 305 generates an LED current control switch signal CS_2 to modulate the conductivity of LED drive current control switch 310. Controller 305 generates a digital LED current control signal CS_{2D} that is amplified by buffer 309 to generate LED current control switch control signal CS_2. Controller 305 includes a buffer 309 to provide the drive current for LED current control switch signal CS_2. Buffer 309 operates from a high side voltage supply rail of less than or equal to auxiliary voltage V_{AUX} and from a low side voltage supply rail of common voltage V_{com}. In at least one embodiment, LED current control switch signal CS_2 is a duty cycle modulated gate drive signal. The duty cycle modulated gate drive signal modulating the conductivity of switch 310 controls the LED current i_{LED} supplied by switching power converter 303. The current i_{LED} serves as the drive current for switching LED system 304. Adjusting the current i_{LED} modifies the intensity of switching LED light system 304. The controller 305 modulates the conductivity of switch 310 so that an average LED current i_{LED} causes each LED in the switching LED system 304 to illuminate at a desired intensity level. In a non-dimmed configuration of LED lighting system 300, the desired intensity level is, for example, the full (100%) rated intensity of the LED(s) of the switching LED system 304 or zero (0) intensity (off).

As subsequently described in more detail, to regulate the LED drive current i_{LED}, the controller 305 receives a LED feedback signal $LEDi_{sense}$ from a current sense device 314. In at least one embodiment, the feedback signal $LEDi_{sense}$ is the current i_{LED} or a scaled version of the current i_{LED}. In another embodiment, the feedback signal $LEDi_{sense}$ is a voltage that is directly proportional to the current i_{LED}. The controller 305 responds to the feedback signal $LEDi_{sense}$ by modifying the current delivered to the switching LED system 304 to maintain a desired LED current i_{LED} and desired link voltage V_{C1}. The current sense device 314 can be any device capable of sensing the LED current i_{LED}. In at least one embodiment, current sense device 314 is a resistor, and the feedback signal $LEDi_{sense}$ is a voltage sensed across the resistor. In at least one embodiment, the feedback signal $LEDi_{sense}$ is sensed by a magnetic current sensor in the proximity of current flowing through an inductor (such as inductor 606 of FIG. 6A or inductor 612 of FIG. 6B) in switching LED system 304. In at least one embodiment, current sense device 314 is a current mirror circuit. Current mirrors are generally not used in high voltage applications. Controller 305 can generate LED current control switch signal CS_2 in any of a variety of ways. Melanson III describes an exemplary system and method for generating LED current control switch signal CS_2.

In at least one embodiment, LED lighting system 300 can dim the LED(s) of switching LED system 304, i.e. adjust the intensity of the LED(s) of switching LED system 304, in response to a dimmer signal D_V. The dimmer signal D_V can be a digital dimming signal $D_{V\_digital}$ or an analog dimming signal D_{V_analog} indicating a dimming level for switching LED system 304. Values of dimmer signal D_V function as a target reference and are compared with $LEDi_{sense}$ external to controller 305 or an integral part of an integrated circuit version of controller 305. In at least one embodiment, the controller 305 adjusts LED current control switch signal CS_2 to minimize a difference between the comparison between the dimmer signal D_V and the feedback signal $LEDi_{sense}$. In at least one embodiment, the dimmer signal D_V is generated and detected as described in Melanson I and Melanson II.

In at least one embodiment, the dimmer signal D_V represents a mapping of a conventional, duty cycle modified dimmer signal to predetermined values different than the dimming level represented by the dimmer output signal value. In

at least one embodiment, a conventional dimmer 320 generates a dimming signal V_{DIM}. The dimming signal V_{DIM} is, for example, a duty cycle modified (i.e. phase-cut) analog signal whose duty cycle or phase angle represents a dimming level. Mapping system 322 includes a lighting output function that converts the dimmer levels indicated by dimming signal V_{DIM} to a digital dimming signal $D_{V\_digital}$ having values that map measured light levels to perception based light levels as described in conjunction with the exemplary systems and methods of Melanson I and Melanson II. In at least one embodiment, controller 305 uses the digital dimming signal $D_{V\_digital}$ directly to generate LED current control switch signal CS_2. In at least one embodiment, digital-to-analog converter (DAC) 324 converts the digital dimming signal $D_{V\_digital}$ into a corresponding analog dimming signal D_{V_analog}. The digital and analog versions of dimming signal D_V are generically referred to here as dimming signal D_V. Dimmer 320, mapping system 322, and DAC 324 are shown in "dashed lines" because dimming is optional for LED lighting system 300.

FIG. 4 depicts a LED lighting system 400, which represents one embodiment of LED lighting system 300. LED lighting system 400 includes switching power converter 402 to convert the rectified input voltage V_x into an approximately DC link voltage V_{C1}. Switching power converter 402 and controller 305 also provide power factor correction. The switching power converter 402 includes a switch 308 that turns 'on' (conducts) and turns 'off' (nonconductive) in response to a PFC control signal CS_1 generated by PFC and output voltage controller 305. When switch 308 is 'on', inductor 408 energizes with the current I_{L1} from the full-bridge diode rectifier 103. When switch 308 is 'off', the inductor 408 drives current I_{L1} through diode 412 to charge capacitor 408. The PFC control signal CS_1 varies the duty cycle of switch 308 so that the DC voltage link voltage V_{C1} on storage capacitor 408 averages to a desired value of DC voltage V_{C1}. In at least one embodiment, steady state voltage V_{C1} has an average value in the range of 200 V to 400V. In at least one embodiment, current I_{L1} represents current i_{in} of FIG. 3. PFC and output voltage controller 305 operates as previously described to control the duty cycle of switch 308 such that current I_{L1} is linearly proportional to the input voltage V_x. Capacitor 432 provides filtering to smooth inductor current I_{L1} so that the average inductor current I_{L1} is sinusoid in phase with input signal V_x.

Controller 305 generates LED current control switch signal CS_2 based on the value of the comparator 438 output signal V_{comp}. In at least one embodiment, comparator output signal V_{comp} is a voltage representing a logical "1" if the value of feedback signal $LEDi_{sense}$ is greater than an analog value of dimmer signal D_{V_analog}. Otherwise, the value of comparator output signal V_{comp} is a logical "0". The dimmer signal D_V is a target reference value, and controller 305 generates controls signal CS_2 to modify the current i_{LED} to minimize differences between feedback signal $LEDi_{sense}$ and dimmer signal D_{V_analog}. The dimmer signal D_{V_analog} is scaled so that when the difference between feedback signal $LEDi_{sense}$ and dimmer signal D_V analog is minimized, the intensity of the LED(s) of switching LED system 304 matches the dimming level indicated by dimmer signal D_V analog. As the dimming level indicated by dimmer signal D_V analog changes, the value of comparator output signal V_{comp} also changes so that controller 305 causes LED current control switch signal CS_2 to track the changes in dimming level indicated by dimmer signal D_{V_analog}. As previously described, in at least one

embodiment, controller 305 uses the comparator output signal V_{comp} to generate LED current control switch signal CS_2 as described in Melanson III.

FIGS. 6A and 6B depict exemplary embodiments of switching LED system 304. Switching LED system 600 includes one or more LED(s) 602. The LED(s) 602 can be any type of LED including white, amber, other colors, or any combination of LED colors. Additionally, the LED(s) 602 can be configured into any type of physical arrangement, such as linearly, circular, spiral, or any other physical arrangement. In at least one embodiment, each of LED(s) 602 is serially connected. Capacitor 604 is connected in parallel with LED(s) 602 and provides filtering to protect the LED(s) 602 from AC signals. Inductor 606 smooths energy from LED current i_{LED} to maintain an approximately constant current i_{LED} when switch 310 conducts. Diode 608 allows continuing current flow when switch 310 opens.

In switching LED system 610, inductor 612 is connected in series with LED(s) 602 to provide energy storage and filtering. Inductor 612 smoothes energy from LED current i_{LED} to maintain an approximately constant current i_{LED} when switch 310 conducts. Diode 614 allows continuing current flow when switch 310 opens. Although two specific embodiments of switching LED system 304 have been described, switching LED system 304 can be any switching LED system.

FIG. 7 depicts a graphical relationship 700 between the comparator voltage V_{COMP}, LED current control switch signal CS_2, and current $i_{LEDsense}$ (FIG. 4). When LED current control switch signal CS_2 is high, switch 310 conducts, and LED current i_{LED} increases. When the comparator voltage V_{COMP} goes high, PFC and output voltage controller 305 keeps LED current control switch signal CS_2 high until the comparator voltage V_{COMP} goes low again. In this manner, the average current $i_{LEDsense}$, and, thus, the average LED current i_{LED}, is responsive to the dimmer signal Dv, and, thus, the intensity of the LED(s) in switching LED system are also responsive to dimmer signal Dv.

FIG. 8 depicts a graphical relationship 800 between LED current control switch signal CS_2 and current i_{LED}. The LED current i_{LED} ramps up when LED current control switch signal CS_2 is high (i.e. causes switch 310 to conduct) and ramps down when LED current control switch signal CS_2 is low (i.e. causes switch 310 to turn 'off'). The average current i_{LED} tracks the dimmer signal Dv. The intensity of switching LED system 304 is approximately directly proportional to the driving LED current i_{LED}.

FIG. 9 depicts one embodiment of a spread spectrum system 900. The spread spectrum system can be included as part of controller 305 or can be constructed using separate discrete components as a separate IC. Spread spectrum system 900 can also be implemented as code stored in a computer readable medium and executable by controller 405. In general, spread spectrum system 900 receives an input signal T_{Target} and generates an output signal T_{OUT}. Output signal T_{OUT} randomly varies from input signal T_{Target} within a predetermined range set by Δ_{max}, and an average value of output signal T_{OUT} equals input signal T_{Target}. Input signal T_{Target} is, for example, a pulse width of control signals CS_1 and/or CS_2. The value of Δ_{max} is, for example, +/−10% of a nominal value of PFC control signal CS_1. Multiple spread spectrum system 900 can be used by controller 305 to spread the spectrum of multiple input signals such as the pulse widths of control signals CS_1 and CS_2.

Spread spectrum system 900 includes a delta-sigma modulator 901. Delta-sigma modulator 901 includes an adder 902 that adds the current value of input signal T_{Target} to a negative value of the previous value of output signal T_{OUT} to generate

a difference signal T_{Diff}. In at least one embodiment, spread spectrum system **900** is initialized as startup with output signal $T_{OUT}=0$. The difference signal T_{Diff} is processed by loop filter **904** to generate a loop filter output signal U.

The values of delta-sigma modulator output signal T_{OUT} are randomized around the values of input signal T_{Target}. A random number generator **906** generates random output values of random signal RN that are multiplied by Δ_{max} to generate random signal RN'. During each cycle of spread spectrum system **900**, adder **910** adds the random signal RN' to the loop filter output signal U, and quantizer **912** quantizes the sum of RN' and U to generate the quantization output signal T_{OUT}. Random Number Generator **906** has predetermined value ranges set by a range limiting value Δ_{max}. In at least one embodiment, RN' varies approximately 10%.

Delta-sigma modulator **901** can be any delta-sigma modulator such as any first order or multi-order delta-sigma modulator described in, for example, *Understanding Delta-Sigma Data Converters* by Schreier and Temes, IEEE Press, 2005, ISBN 0-471-46585-2 or as available from Cirrus Logic Inc. of Austin, Tex., U.S.A. The delta-sigma modulator **901** provides noise-shaping and seeks to consistently generate values of delta-sigma output signal T_{OUT} that minimize the difference between output signal T_{OUT} and difference signal T_{Diff}. Thus, delta-sigma modulator **901** helps ensure that the average output signal T_{OUT} equals the average input signal T_{Target}.

FIG. **10** depicts one embodiment of a feed forward lighting power and control system **1000**. Power and control system **1000** preferably also includes a common reference node for switches **308** and **310** (through current sense device **314**) and controller **1002**. Controller **1002** represents one embodiment of controller **305**. Controller **1002** is logically divided into two separate control systems, PFC control system **1004** to control power factor correction and regulate the link voltage V_{C1} of switching power converter **402**, and switching LED system controller **1006** to control the LED current i_{LED} and, thus, control the intensity (i.e. brightness) of switching LED system **304**.

The power and control system **1000** utilizes feed forward control so that PFC controller **1004** can more rapidly respond to changing power demands of Switching LED system light source **304** due to dimming. When dimmer signal Dv indicates a change in the dimming level of light source **304**, switching LED system controller **1006** responds to dimming signal Dv by decreasing the pulse width of duty cycle modulated LED current control switch signal CS_2 to reduce the average values of current i_{LED}. Decreasing current i_{LED} reduces the power demand of light source **304**.

Feed forward control allows PFC system controller **1004** to anticipate power demand changes of light source **304** due to, for example, dimming. The PFC system controller **1004** is configured to provide a specific output voltage link voltage V_{C1} for a specific dimming level. In at least one embodiment, the controller **1004** responds to comparison signal V_{comp}, which indicates a change in requested dimming level and, thus, a change in power demand by light source **304** by proportionately changing the pulse width of LED current control switch signal CS_2. In at least one embodiment, the dimmer signal Dv is provided directly to controller **1004** as shown by the dashed line **1008**. However, providing dimmer signal Dv to controller **1004** may require an extra pin for controller **1002**, which generally adds cost to controller **1002**. Using feed forward control, the controller **1002** can concurrently modify power demand by the power factor correction control system **1004** and modify power supplied by the

switching LED system controller **1006**. The term "concurrently" includes short delays due to, for example, processing by controller **1006**.

In accordance with changes in a dimming level indicated by the dimmer signal Dv, in at least one embodiment, the PFC system controller **1004** includes a proportional integrator (PI) compensator **1010** that receives a feedback signal link voltage V_{C1} representing the link voltage V_{C1} and generates an output signal using a PI transfer function, such as the PI transfer function and system of Melanson IV. However, because the dimmer signal D_V anticipates power demand by light source **304**, the PFC controller **1004** can concurrently respond to dimming level changes and, the PI compensator **1010**, in at least one embodiment, only makes power demand adjustments of, for example, 10% of the total power delivered by the power and control system **1000**. Responding more rapidly to power demand changes in light source **304** allows switching power converter **402** to utilize a smaller capacitor value, such as 4.7 µF for capacitor **408** because increases of link voltage V_{C1} are reduced to within the operating characteristics of ceramic, polypropylene, and other capacitors that have advantageous properties relative to electrolytic capacitors such as better temperature characteristics because light source **304** tends to generate higher temperatures better suited for ceramic, polypropylene, and other higher temperature capacitors. In at least one embodiment, controller **1004** generates PFC control signal CS_1 in the same manner as controller **305** so that the changes in the dimming level indicated by dimmer signal D_V are commensurate with changes to the power ($V_{C1} \cdot i_{in}$) delivered by switching power converter **402** while maintaining an approximately constant link voltage V_{C1}.

FIG. **11** depicts a switching light source bank **1100** having N+1 switching LED systems, where N is an integer greater than or equal to 1. Switching LED system bank **1100** is a substitution for switching LED system **304**. In at least one embodiment, each light source **304.**x is a light source such as switching LED system **304**, where x denotes the xth light source and is, for example, an integer and a member of the set $\{0, \ldots, N\}$. Each of the N+1 light sources includes at least one LED and the number and color of each LED for each light source is a matter of design choice. Each light source **304.**x is connected to a respective switch **1104.**x, and each switch **1104.**x is an n-channel FET. In at least one embodiment, controller **305** independently controls each light source **304.**x by generating respective control signals $CS_2.0, \ldots, CS_2.N$ to control the conductivity of switches **1104.0, ..., 1104N**. The average values of the drive currents $i_{LED}.0, \ldots, i_{LED}.N$ control the respective intensity of LED(s) of switching LED systems **304.0, ..., 304.N**. Switching LED systems **304.0, ..., 304.N** are connected to respective current sense elements **314.0, ..., 314.N**.

The current sense elements **314.0, ..., 314.N** can be different or identical. Each current sense element **314.**x provides a feedback signal LEDsense.x to controller **305**. In at least one embodiment, controller **305** generates each control signal $CS_2.x$ in the same manner as the generation of LED current control switch signal CS_2 (FIG. **4**). The output signals of $LEDi_{sense}.0, \ldots, LEDi_{sense}.N$ are fed back to controller **305** to allow controller **305** to adjust the switching frequency of switches **1104.0, ..., 1104.N** and, thus, correlate LED drive currents $i_{LED}.0, \ldots, i_{LED}.N$ with a desired intensity of the LED(s) of light sources **304.0, ..., 304.N**. In at least one embodiment, the desired intensity is a dimming level indicated by dimmer signal D_V. The type, number, and arrangement of LED(s) in switching LED systems **304.0, ..., 304.N** is a matter of design choice and depends, for example, on the

range of desired intensity and color temperatures of switching LED systems 304.0, . . . , 304.N.

FIG. 12 depicts a switching LED system bank 1200, which represents a substitution for switching LED system 304 (FIG. 4). One current sense element 312 provides a feedback signal $LEDi_{sense}$ that represents the LED sense currents of all switching LED systems 304.0, . . . , 304.N to sense each of the LED sense currents $i_{LEDsense}.0, . . . , i_{LEDsense}.N$ for respective switching LED systems 304.0, . . . , 304.N. Each of the switches 1204.0, . . . , 1204.N have a common current node 1206. At the common current node 1206, all of the LED sense currents $i_{LEDsense}.0, . . . , i_{LEDsense}.N$ are combined, and the feedback signal $LEDi_{sense}$ from current sense device 312 represents the combination of all of the LED sense currents $i_{LEDsense}.0, . . . , i_{LEDsense}.N$. In at least one embodiment, feedback signal $LEDi_{sense}=1/x·(i_{LEDsense}.0+i_{LEDsense}.1+, . . . , +i_{LEDsense}.N)$, where "x" is a scaling factor of current sense device 312. Utilizing a common sense element 312 reduces a number of pins for an integrated circuit implementation of controller 1208, which reduces the cost of controller 1208. Controller 1208 represents one embodiment of controller 305.

FIG. 13 depicts a graphical representation 1300 of non-overlapping control signals and current sense signals. The operation of LED source bank 1200 and controller 1208 (FIG. 12) are described in conduction with the signals of FIG. 13. Control signals $CS_2.0$ and $CS_2.N$ represent two exemplary control signals for control signals $CS_2.0, . . . , CS_2.N$. Control signals $CS_2.0$ and $CS_2.N$ are depicted with a duty cycle of 0.25, i.e. pulse width/period, and non-overlapping pulse widths. During each pulse of control signals $CS_2.0$ and $CS_2.N$, respective currents $i_{LEDsense}.0$ and $i_{LEDsense}.N$ flow through respective switches 1204.0 and 1204.N and are combined into the single $LEDi_{sense}$ feedback signal from current sense device 312.

Referring to FIGS. 12 and 13, controller 1208 includes an LED current detector 1210 that detects and determines the individual LED currents i_{LED} in switching LED systems 304.0, . . . , 304.N from the $LEDi_{sense}$ feedback signal. The location in time of each contribution of currents $i_{LEDsense}.0$ and $i_{LEDsense}.N$ in the feedback signal $LEDi_{sense}$ corresponds to the respective pulses of controls signals $CS_2.0$ and $CS_2.N$.

In at least one embodiment, in a dimmable configuration, dimmer signal D_V is used to indicate a dimming level for switching LED systems 304.0, . . . , 304.N. Comparator 438 compares the $LEDi_{sense}$ feedback signal to the dimmer signal D_V. Variations in the comparator output signal Vcomp occur at approximately the same time as the contribution of currents $i_{LEDsense}.0$ and $i_{LEDsense}.N$ to the feedback signal $LEDi_{sense}$. Since controller 1208 generates control signals $CS_2.0$ and $CS_2.N$, the times at which currents $i_{LEDsense}.0$ and $i_{LEDsense}.N$ will vary the comparator output signal V_{comp} are also known by LED current detector 1210. By knowing which changes in comparator output signal V_{comp} correspond to each particular current of switching LED systems 304.0, . . . , 304.N, controller 1208 can adjust each LED current control switch signal $CS_2.0$ and $CS_2.N$ in response to the dimmer signal D_V to dim the LEDs of switching LED systems 304.0 and 304.N to the dimming level indicated by dimmer signal D_V. In at least one embodiment, controller 1208 generates each LED current control switch signal $CS_2.0, . . . , CS_2.N$ in any manner described in conjunction with controller 305.

In at least one embodiment, the switching LED systems 304.0, . . . , 304.N are not dimmed. In this embodiment, LED current detector 1210 receives the feedback signal $LEDi_{sense}$ directly. Since controller 1208 generates control signals $CS_2.0$ and $CS_2.N$, the times at which currents $i_{LEDsense}.0$ and

$i_{LEDsense}.N$, LED current detector 1210 detects the contribution of currents $i_{LEDsense}.0$ and $i_{LEDsense}.N$ during any of the respective times during which respective control signals $CS_2.0$ and $CS_2.N$ are non-overlapping.

FIG. 14 depicts a graphical representation 1400 of overlapping control signals and current sense signals for processing by controller 1208 to generate multiple control signals for multiple light sources from a single feedback signal $LEDi_{sense}$. The overlapping control signals each have a duty cycle of 0.5. LED current detector 1210 detects the contributions of currents $i_{LEDsense}.0$ and $i_{LEDsense}.N$ in feedback signal $LEDi_{sense}$ or comparator output signal V_{comp} at times when the control signals $CS_2.0$ and $CS_2.N$ are non-overlapping. For example, LED current detector 1210 detects the contribution of $i_{LEDsense}.0$ during times t_1 to t_2, t_5 to t_6, t_9 to t_{10}, and so on. Likewise, LED current detector detects the contribution of $i_{LEDsense}.N$ during times t_3 to t_4, t_7 to t_8, and so on.

FIG. 15 depicts lighting system 1500, which is one embodiment of lighting system 300. Lighting system 1500 includes PFC switch 1502, which is an n-channel FET and represents one embodiment of switch 308. PFC switch 1502 operates between the primary supply voltage V_x and the common reference voltage V_{com}. PFC switch 1502 does not have to be connected directly to the primary supply voltage V_x. In at least one embodiment, PFC switch 1502 is coupled through other components (not shown) to a primary supply voltage node 1506 conducting primary supply voltage V_x. Lighting system 1500 also includes LED drive current control switch 1504, which is an n-channel FET and represents one embodiment of switch 310. LED drive current control switch 1504 is coupled through switching LED system 304 to link voltage node 1508. LED drive current control switch 1504 operates between the link voltage V_x and the common reference voltage V_{com}. Voltages V_x and V_{C1} are both switching power converter voltages and are collectively referred to as "high" supply voltages 1510 because they represent the highest voltages in the lighting system 1500. Nodes 1506 and 1508 are referred to as high voltage source nodes. PFC switch 1502 is, thus, referred to as a high voltage PFC switch, and LED current control switch 1504 is, thus, referred to as a high voltage LED current control switch. In at least one embodiment, the root mean square (RMS) of high supply voltages 1510 is greater than or equal to 100 V.

The lighting system 1500 also includes PFC and output voltage controller 1512, which in at least one embodiment is identical to controller 305. PFC and output voltage controller 1512 operates from at least two different voltages, which are lower than the high voltages 1510. Output buffers 307 and 309 operate between voltages V_B and the common reference voltage. Voltage V_B is less than or equal to auxiliary voltage V_{AUX} and greater than or equal the digital voltage reference V_D. The voltage V_B is set to be sufficient to drive the gates of switches 1502 and 1504 and, thus, control the conductivity of switches 1502 and 1504. Voltage V_B is referred to as a "medium level" supply voltage. In at least one embodiment, the medium level supply voltage is in the range of 8 V to 50 V.

The lighting system 1500 also includes a digital signal processor (DSP) 1514 to generate PFC control signal CS_{1D} and LED current control signal CS_{2D}. The DSP 1514 is coupled to an LED feedback node 1518. DSP 1514 operates between a digital supply voltage V_D and the common reference voltage V_{com}. The digital supply voltage V_D is sufficient to operate the digital components of DSP 1504 and is, for example, in the range of 3 V to 8 V. A level shifter (LS) 1516 level shifts the digital PFC control signal CS_{1D} and digital LED current control signal CS_{2D} from DSP 1504 to a level sufficient to control the conductivity of respective buffers 307

and **309**. The digital supply voltage V_D can be a stepped down version of the auxiliary voltage V_{AUX} generated internally by controller **1512**.

Thus, although the controller **1512** operates from a digital voltage V_D, and an auxiliary voltage V_{AUX} and the switches operates from high voltages **1510**, the lighting system **1500** has a common reference voltage V_{com} to allow all the components of lighting system **1500** to work together. By operating from auxiliary voltage V_{AUX}, the controller **1512** can be fabricated using lower cost fabrication techniques than a controller operating from the high voltages **1510**.

Thus, in at least one embodiment, a LED lighting system controller operates from a supply voltage V_{AUX} less than a link voltage V_{C1} generated by the LED lighting power system relative to a common reference voltage at a common reference node. By utilizing a lower voltage, in at least one embodiment, the controller can be manufactured at a lower cost than a comparable controller supplied by the primary power supply utilized by the LED lighting power system. Additionally, during normal operation of the LED lighting system, a power factor correction (PFC) switch and an LED drive current switch of the LED lighting system, that respectively control power factor correction and LED drive current, are coupled to the common reference node and have control node-to-common node, absolute voltage that allows the controller to control the conductivity of the switches. In at least one embodiment, the PFC switch and the LED drive current switch each have a control node-to-common node, absolute voltage within 15% of an absolute value of the link voltage relative to the common reference voltage. In at least one embodiment, the LED lighting system utilizes feed forward control to concurrently modify power demand by the LED lighting power system and power demand of one or more switching LED systems. In at least one embodiment, the LED lighting system utilizes a common current sense device to provide a common feedback signal to the controller representing current in at least two of the switching LED systems.

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 light emitting diode (LED) lighting system comprising:
   a power factor correction (PFC) and LED drive controller, the controller comprising:
   a digital signal processor, coupled to the LED feedback node and configured to:
      operate from a digital level supply voltage;
      generate a PFC control signal; and
      generate an LED current control signal;
   a first buffer, coupled to the processor, and configured to:
      operate from a medium level supply voltage, wherein the medium level supply voltage is greater than the digital level supply voltage;
      receive the PFC control signal; and
      convert the PFC control signal into a PFC switch control signal to control conductivity of a high voltage PFC switch; and
   a second buffer, coupled to the processor, and configured to:
      operate from the medium level supply voltage;
      receive the LED current control signal; and
      convert the LED current control signal into an LED current control switch signal to control conductivity of a high voltage LED current control switch.

2. The lighting system of claim **1** wherein the controller further comprises:
   an LED feedback node to receive an LED current feedback signal representing one or more current levels in one or more switching LED systems; and
   a voltage feedback node to receive an input voltage feedback signal representing an input voltage level provided to the lighting system;
   wherein the processor is further configured to generate the PFC control signal in response to the input voltage level represented by the input voltage feedback signal and to generate the LED drive current control signal in response to the one or more current levels represented by the LED current feedback signal.

3. The lighting system of claim **1** wherein the digital supply voltage has an absolute value less than or equal to 8 volts, the medium level supply voltage has an absolute value less than or equal to 50 volts, and the high voltage PFC switch is coupled between voltage nodes having a voltage difference during normal operation of the lighting system of at least 100 volts, and the high voltage LED drive current switch is coupled between voltage nodes having a voltage difference during normal operation of the lighting system of at least 100 volts.

4. The lighting system of claim **1** wherein during normal operation of the lighting system, the medium level voltage is less than or equal to approximately 15% of the voltage at the first high voltage source node relative to a voltage at the common voltage reference node.

5. The lighting system of claim **1** further comprising:
   a dimmer signal input to receive a dimmer signal;
   wherein the controller is configured to:
      control power delivered by a switching power converter to a switching LED system; and
      concurrently modify power demand by the power factor correction control system and modify power supplied by the switching power converter in accordance with changes in a dimming level indicated by the dimmer signal.

6. The lighting system of claim **5** wherein the controller comprises a first control module to control power factor correction by the switching power converter and a second control module to control power delivered by the switching power converter and both the first and second control modules include inputs to receive the dimmer signal.

7. The lighting system of claim **1** further comprising:
   a common voltage reference node;
   a first high voltage source node to conduct a primary voltage;
   a second high voltage source node to conduct a link voltage of the lighting system;
   the PFC switch coupled to the common voltage reference node and the first high voltage source node; and
   the LED current control switch to control current to at least one LED, wherein the LED current control switch is coupled to the common voltage reference node and the second high voltage source node;
   wherein, during normal operation of the lighting system, the PFC switch and an LED current control switch of the LED lighting system have respective control node-to-common node, absolute voltages that allow the controller to control the conductivity of the switches and provide power factor correction and supply an approximately constant current to an LED switching system for each dimming level indicated by a dimmer signal.

8. The lighting system of claim **7** wherein the control node-to-common node voltages of the PFC switch and the LED current control switch are less than or equal to 0.15 times a voltage at the first voltage source node relative to a voltage at the common voltage reference node.

9. The lighting system of claim **7** wherein:

the PFC switch and the LED current control switch are members of the group consisting of: field effect transistors and insulated gate bipolar transistors;

the control nodes of the PFC switch and the LED current control switch are members of the group consisting of: a field effect transistor gate node and an insulated gate bipolar transistor gate node; and

the common nodes of the PFC switch and the LED current control switch are members of the group consisting of: a field effect transistor source node and an insulated gate bipolar transistor emitter.

10. The lighting system of claim **7** further comprising:

a third voltage source node to conduct a third voltage, wherein the third voltage is lower than the link voltage and the supply voltage; and

one or more transistors coupled to the third voltage source node and the common voltage reference node, wherein the one or more transistors operate from voltages at the third voltage source node and the common voltage reference node.

11. The lighting system of claim **7** further comprising:

a current sense device coupled to the LED drive current switch node and the common voltage reference node and, during normal operation of the lighting system, having a voltage across the current sense device less than or equal to 0.15 times a voltage at the first voltage source node relative to the voltage at the common voltage reference node and provides a feedback signal for controlling the LED current control switch.

12. The lighting system of claim **11** wherein the current sense device is a resistor.

13. The lighting system of claim **11** further comprising:

a plurality of LED drive current switches, wherein each LED drive current switch controls current to at least one LED and is coupled to the common voltage reference node, the first voltage source node, and the controller; and

a single current sense device coupled to the LED drive current switches, wherein, during normal operation of the lighting system, the current sense device senses current in all of the LED drive current switches and provides a feedback signal for use by the controller to control current in all of the LED current control switches.

14. The lighting system of claim **13** further comprising:

multiple LED chains comprising one or more LEDs, wherein each LED chain is coupled to one of the current sense devices.

15. A method comprising:

operating a digital signal processor of a power factor correction (PFC) and output voltage controller from a digital level supply voltage;

generating a PFC control signal; and

generating an LED current control signal;

operating a first buffer, coupled to the processor, from a medium level supply voltage, wherein the medium level supply voltage is greater than the digital level supply voltage;

receiving the PFC control signal;

converting the PFC control signal into a PFC switch control signal to control conductivity of a high voltage PFC switch; and

operating a second buffer, coupled to the processor, from the medium level supply voltage;

receiving the LED current control signal; and

converting the LED current control signal into an LED current control switch signal to control conductivity of a high voltage LED current control switch.

16. The method of claim **15** wherein the controller includes an LED feedback node to receive an LED current feedback signal representing one or more current levels in one or more switching LED systems and a voltage feedback node to receive an input voltage feedback signal representing an input voltage level provided to the lighting system, the method further comprising:

generating the PFC control signal in response to the input voltage level represented by the input voltage feedback signal; and

generating the LED drive current control signal in response to the one or more current levels represented by the LED current feedback signal.

17. The method of claim **15** wherein the digital supply voltage has an absolute value less than or equal to 8 volts, the medium level supply voltage has an absolute value less than or equal to 50 volts, and the high voltage PFC switch is coupled between voltage nodes having a voltage difference during normal operation of the lighting system of at least 100 volts, and the high voltage LED drive current switch is coupled between voltage nodes having a voltage difference during normal operation of the lighting system of at least 100 volts.

18. The method of claim **15** further comprising:

generating a first voltage, wherein the first voltage is a link voltage;

operating a switching power converter of an LED lighting power system from the first source voltage relative to a common voltage, wherein the switching power converter includes the PFC switch;

operating the PFC switch at a control node-to-common node, absolute voltage to allow the PFC and output voltage controller to control the PFC switch and provide power factor correction for the switching power converter;

operating the LED current control switch at a control node-to-common node, absolute voltage to allow the PFC and output voltage controller to control the LED current control switch to supply an approximately constant current to an LED switching system for each dimming level indicated by a dimmer signal; and

controlling conductivity of the PFC switch and the LED current control switch with the PFC and output voltage controller.

19. The method of claim **18** wherein:

operating the PFC switch of the switching power converter at a control node-to-common node, absolute voltage to allow a PFC and output voltage controller to control the PFC switch and provide power factor correction for the switching power converter comprises operating the PFC switch of the LED lighting power system at a control node-to-common node, absolute voltage less than or equal to 0.15 times the first source voltage relative to the common voltage reference; and

operating the LED current control switch at a control node-to-common node, absolute voltage to allow the PFC and output voltage controller to control the LED current control switch to supply an approximately constant current to an LED switching system for each dimming level indicated by a dimmer signal comprises operating the LED current control switch at a control node-to-com-

mon node, absolute voltage less than or equal to 0.15 times the first source voltage relative to the common voltage reference.

20. The method of claim 18 wherein the PFC and LED current control switches comprise field effect transistors and controlling conductivity of the PFC switch and LED current control switch with the PFC and output voltage controller comprises providing respective duty cycle modified control signals to gates of the PFC switch and LED current control switch.

21. The method of claim 18 further comprising:
receiving a rectified primary supply voltage, wherein a root mean square (RMS) value of the primary supply voltage is greater than the medium level voltage;
boosting the primary supply voltage to the first source voltage, wherein boosting the primary supply voltage further comprises modulating the conductivity of the PFC switch to generate a power factor corrected first source voltage.

22. The method of claim 18 further comprising:
operating additional LED current control switches at respective current node voltages less than or equal to 0.15 times the first source voltage relative to the common voltage reference, wherein each LED current control switch controls current through a respective chain of LEDs and each chain of LEDs includes at least one LED;
receiving feedback signals, wherein each feedback signal represents a respective current conducted by one of the LED current control switches; and
controlling conductivity of each LED current control switch with the PFC and output voltage controller in response to the feedback signal.

23. The method of claim 18 further comprising:
receiving a dimmer signal; and
controlling conductivity of the PFC switch and the LED current control switch further comprises:
concurrently controlling the conductivity of the PFC switch and the LED current control switch to modify power demand by LED lighting power system and modify power supplied by the lighting system in accordance with changes in a dimming level indicated by the dimmer signal.

24. The method of claim 18 wherein the second source voltage is less than or equal to approximately 15% of the first source voltage.

25. The method of claim 18 further comprising:
operating one or more transistors of the PFC and output voltage controller from a third voltage source node and the common voltage reference, wherein the third voltage is lower than the link voltage and the second source voltage.

26. The method of claim 18 wherein a switching LED system includes the LED and controlling conductivity of the LED current control switch further comprises:

receiving a feedback signal from a switching LED system; and
responding to the feedback signal to maintain a predetermined current to each LED.

27. The method of claim 26 further comprising:
sensing a voltage across a resistor representing a current through each LED, wherein the voltage sensed across the resistor is the feedback signal.

28. The method of claim 18 further comprising:
operating additional LED current control switches at respective current node voltages less than or equal to 0.15 times the first source voltage relative to the common voltage reference, wherein each LED current control switch controls current through a respective chain of LEDs and each chain of LEDs includes at least one LED;
receiving a single feedback signal representing current conducted by each LED current control switch; and
controlling conductivity of each LED current control switch with the PFC and output voltage controller in response to the feedback signal.

29. The method of claim 28 wherein controlling conductivity of each LED current control switch with the PFC and output voltage controller in response to the feedback signal comprises:
determining during separate periods of time the respective currents conducted by each LED current control switch.

30. A light emitting diode (LED) lighting system comprising:
an LED lighting power system, wherein during normal operation of the LED lighting system the LED lighting power system generates a first source voltage relative to a common voltage, wherein the first source voltage is a link voltage, and the LED lighting power system includes:
a switching power supply having a power factor correction (PFC) switch, wherein during normal operation of the LED lighting system, the PFC switch of the LED lighting power system operates at a current node voltage less than or equal to 0.1 times the first source voltage relative to the common voltage reference; and
an LED current control switch, wherein during normal operation of the LED lighting system, the LED current control switch operates at a current node voltage less than or equal to 0.1 times the first source voltage relative to the common voltage reference;
a PFC and output voltage controller coupled to conductivity control nodes of the first and LED drive current switches, wherein during normal operation of the lighting control system, the controller operates from a second source voltage relative to the common voltage and controls conductivity of the PFC switch and the LED current control; and
at least one LED coupled to the LED current control switch.

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