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(54) **DEVICE AND METHOD FOR CONTROLLING CURRENT TO SOLID STATE LIGHTING CIRCUIT**

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H05B 33/08 (2006.01)

(52) **U.S. Cl.**
CPC ***H05B 33/0815*** (2013.01); ***H05B 33/0812*** (2013.01); *Y02B 20/343* (2013.01); *Y02B 20/345* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,107,757	A *	8/1978	Masuda et al.	96/82
5,065,209	A *	11/1991	Spratt et al.	257/588
6,016,038	A	1/2000	Mueller et al.	
6,211,626	B1	4/2001	Lys et al.	
6,212,082	B1	4/2001	Bailly	
2008/0116818	A1 *	5/2008	Shteynberg et al.	315/192
2008/0272651	A1	11/2008	Fong	
2009/0146575	A1	6/2009	Chu et al.	

(Continued)

FOREIGN PATENT DOCUMENTS

CN	201365204	Y	12/2009
DE	102008039409	A1	2/2010

(Continued)

OTHER PUBLICATIONS

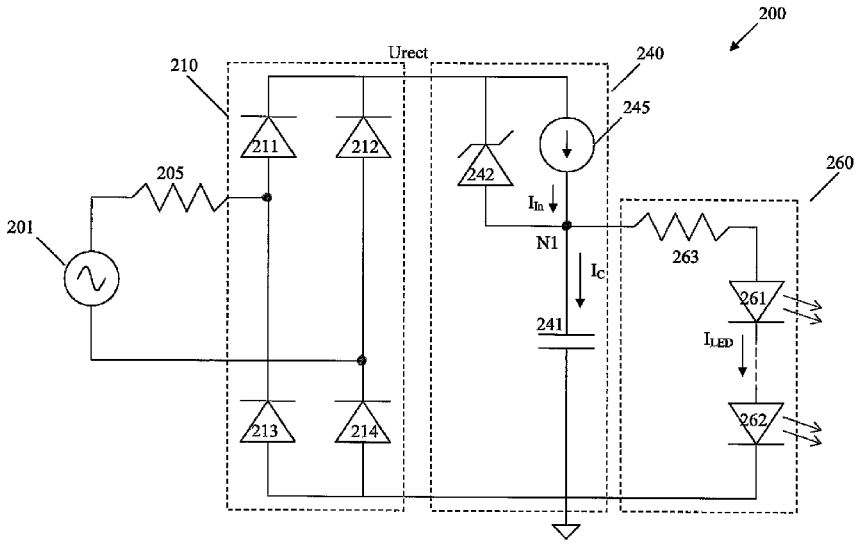
Mhoamed Z. Youssef et al; "A Universal Single-Stage AC-DC Front-End Resonant Converter With a New Active Current Mode Controller: Performance and Design", IEEE, 2007, SC 1,2 & 4 pp. 790-796.

Primary Examiner — Long Nguyen

(57) **ABSTRACT**

A device for controlling current to a solid state lighting load includes a capacitor (**241**, **341**) and a current source (**245**, **345**). The capacitor is connected in a parallel arrangement with the solid state lighting load (**260**, **360**). The current source is connected in series with the parallel arrangement of the capacitor and the solid state lighting load. The current source is configured to modulate dynamically an amplitude of an input current provided to the parallel arrangement of the capacitor and the solid state lighting load based on an input voltage.

20 Claims, 6 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2009/0212721	A1	8/2009	Maruyama	
2009/0316442	A1	12/2009	Elferich	
2010/0207536	A1*	8/2010	Burdalski et al.	315/224
2010/0320944	A1*	12/2010	Romer	318/380

FOREIGN PATENT DOCUMENTS

JP	11307815	A	11/1999
WO	2009001279	A1	12/2008
WO	2010027254	A1	3/2010
WO	2010038190	A1	4/2010

* cited by examiner

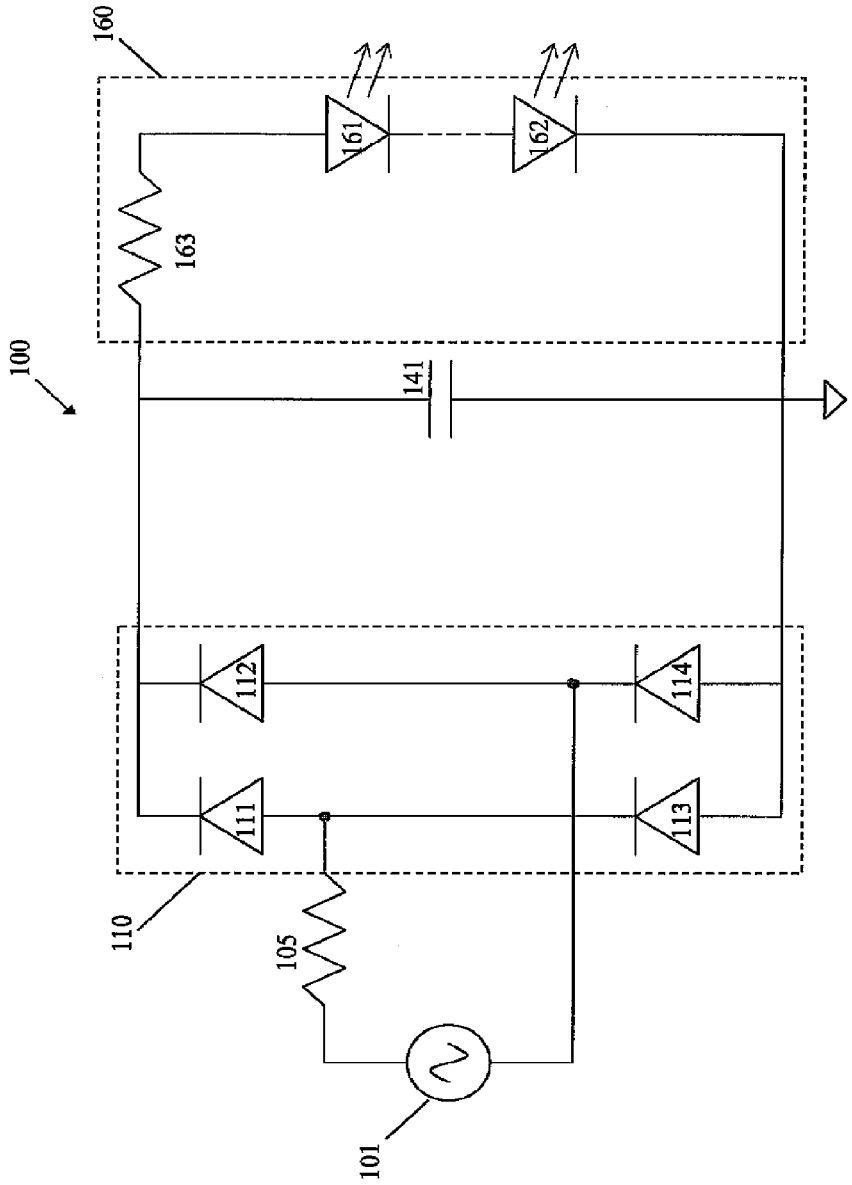


FIG. 1
PRIOR ART

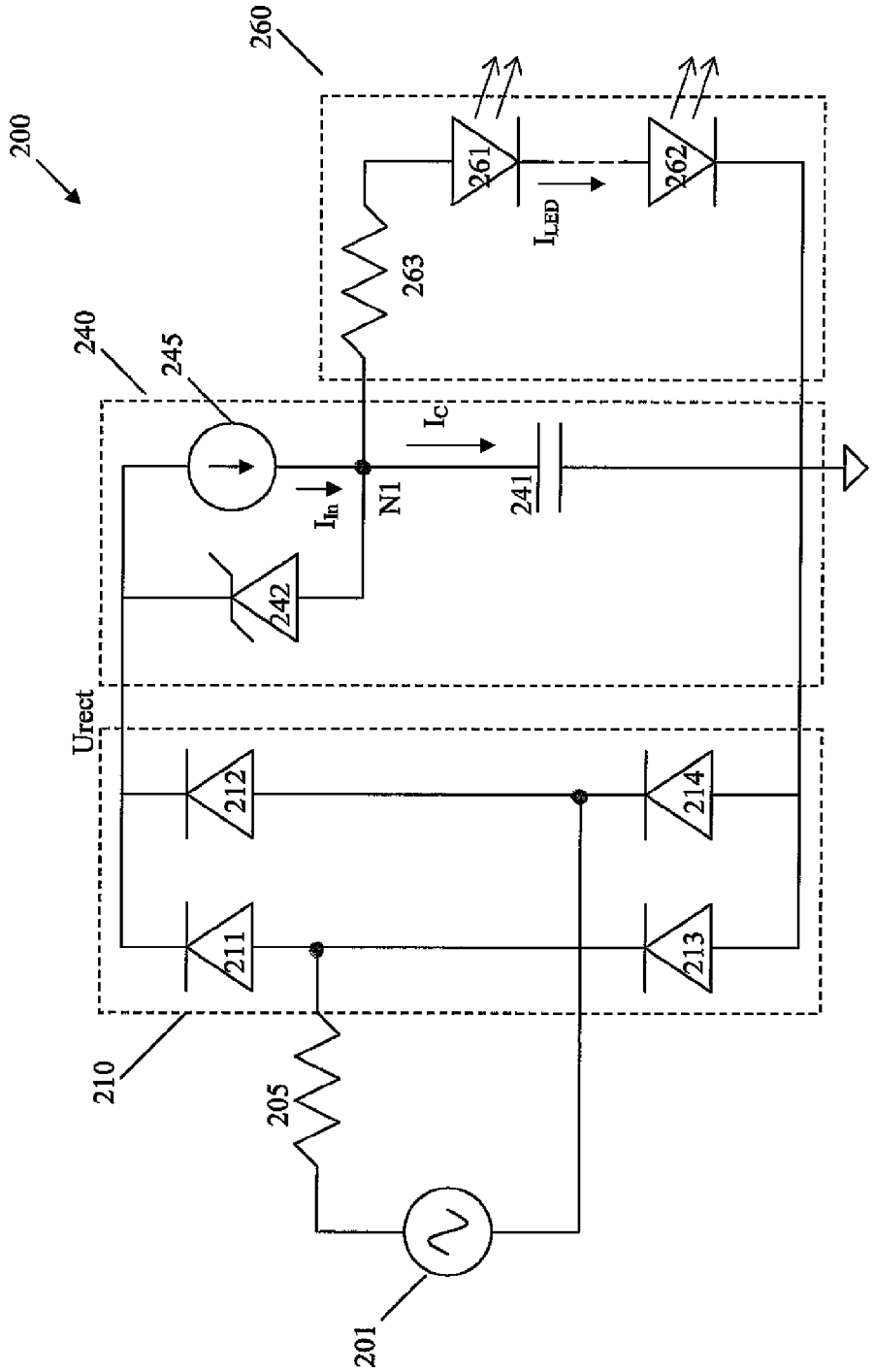

200
260
261
262
263
I_{LED}
240
245
I_C
241
I_{In}
N1
242
Urect
212
214
211
213
210
205
201

FIG. 2

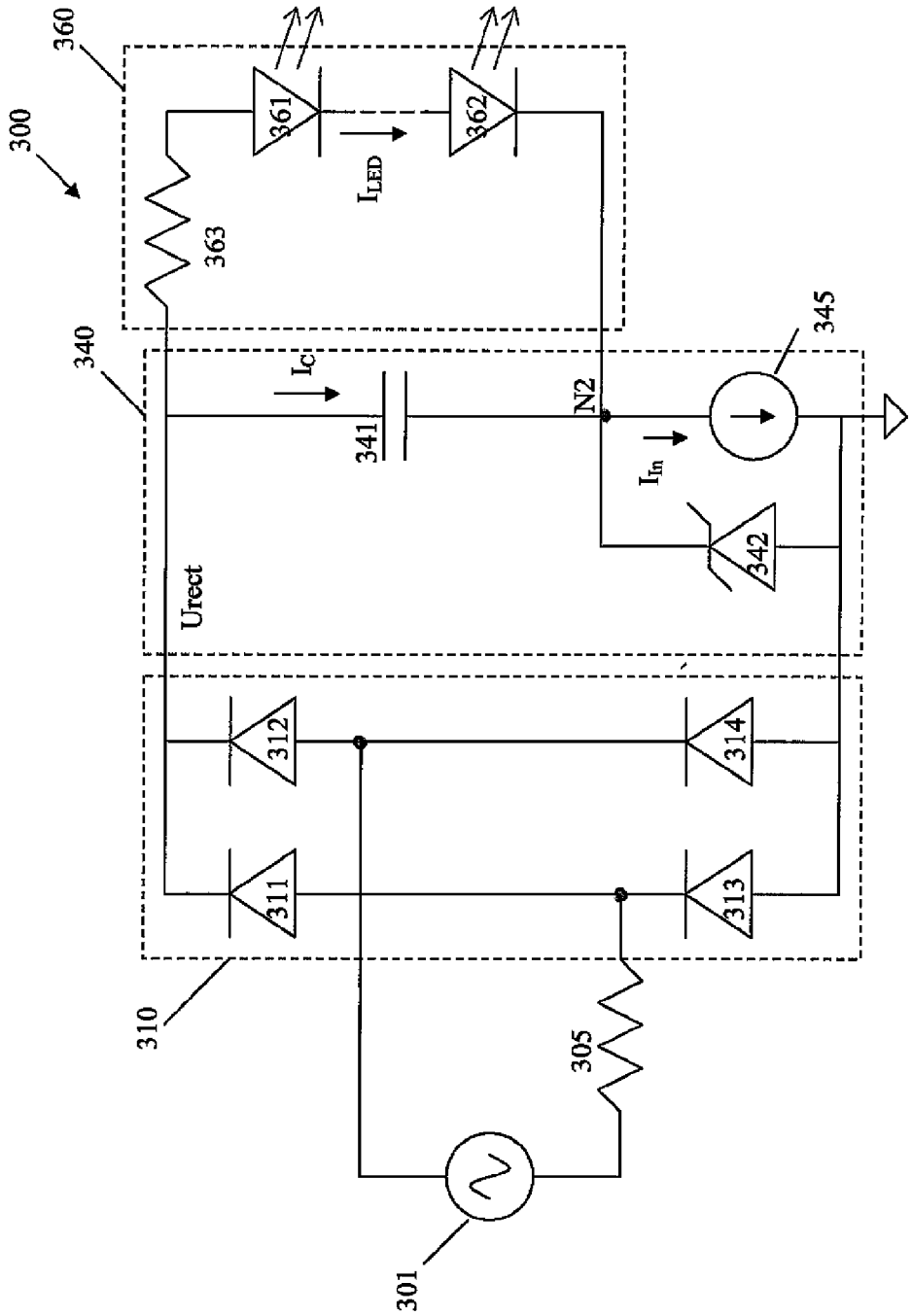

300
360
361
362
I_{LED}
363
340
345
I_C
341
N2
I_{in}
342
Urect
312
314
311
313
310
305
301

FIG. 3

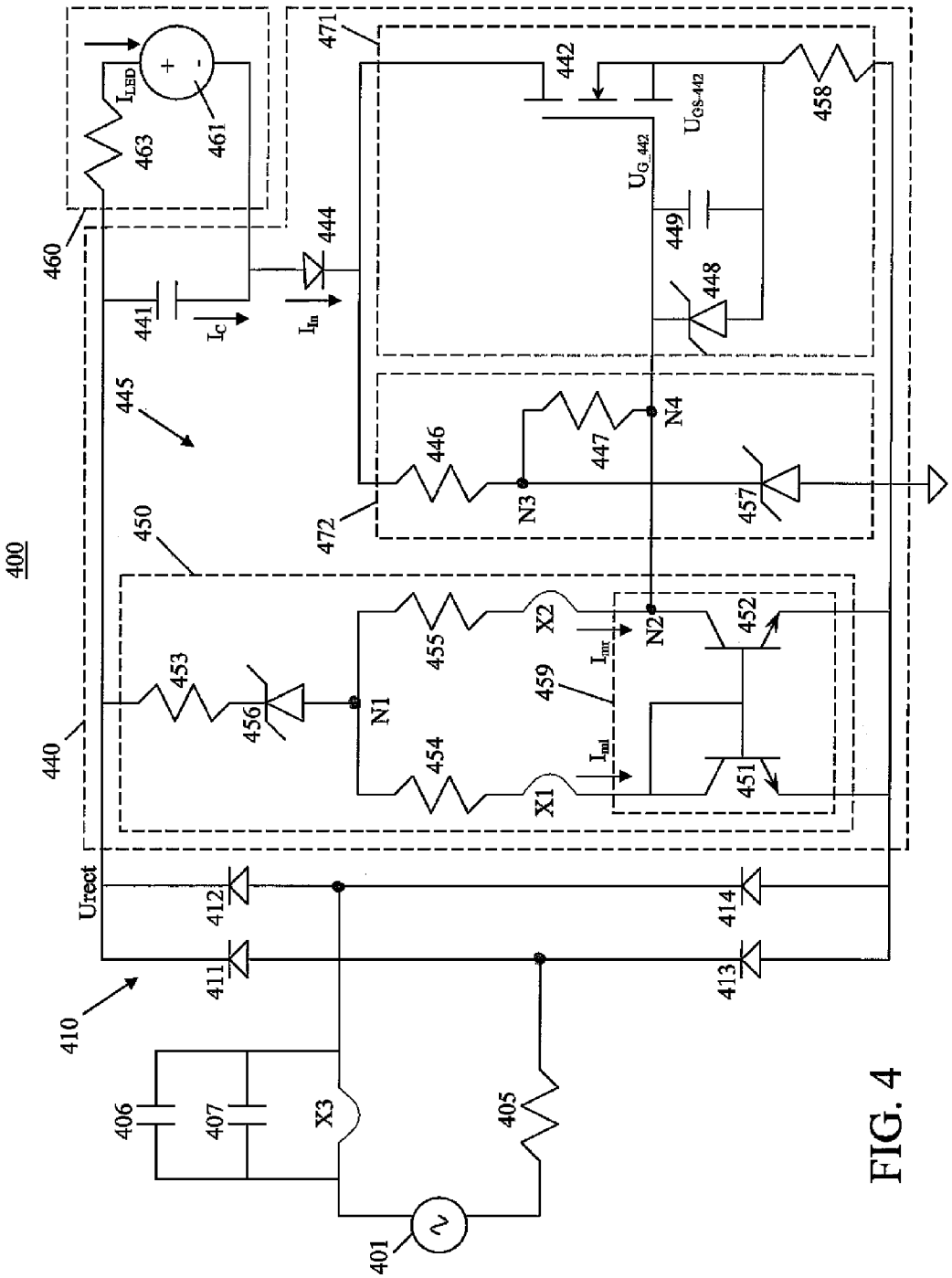

400
410
401
405
406
407
X3
411
412
413
414
Urect
440
450
451
452
453
454
455
456
459
N1
N2
X1
X2
I_{ml}
I_{mr}
445
446
447
N3
N4
457
472
441
I_C
I_{in}
444
460
461
I_{LED}
463
471
442
U_{G_442}
U_{GS-442}
448
449
458

FIG. 4

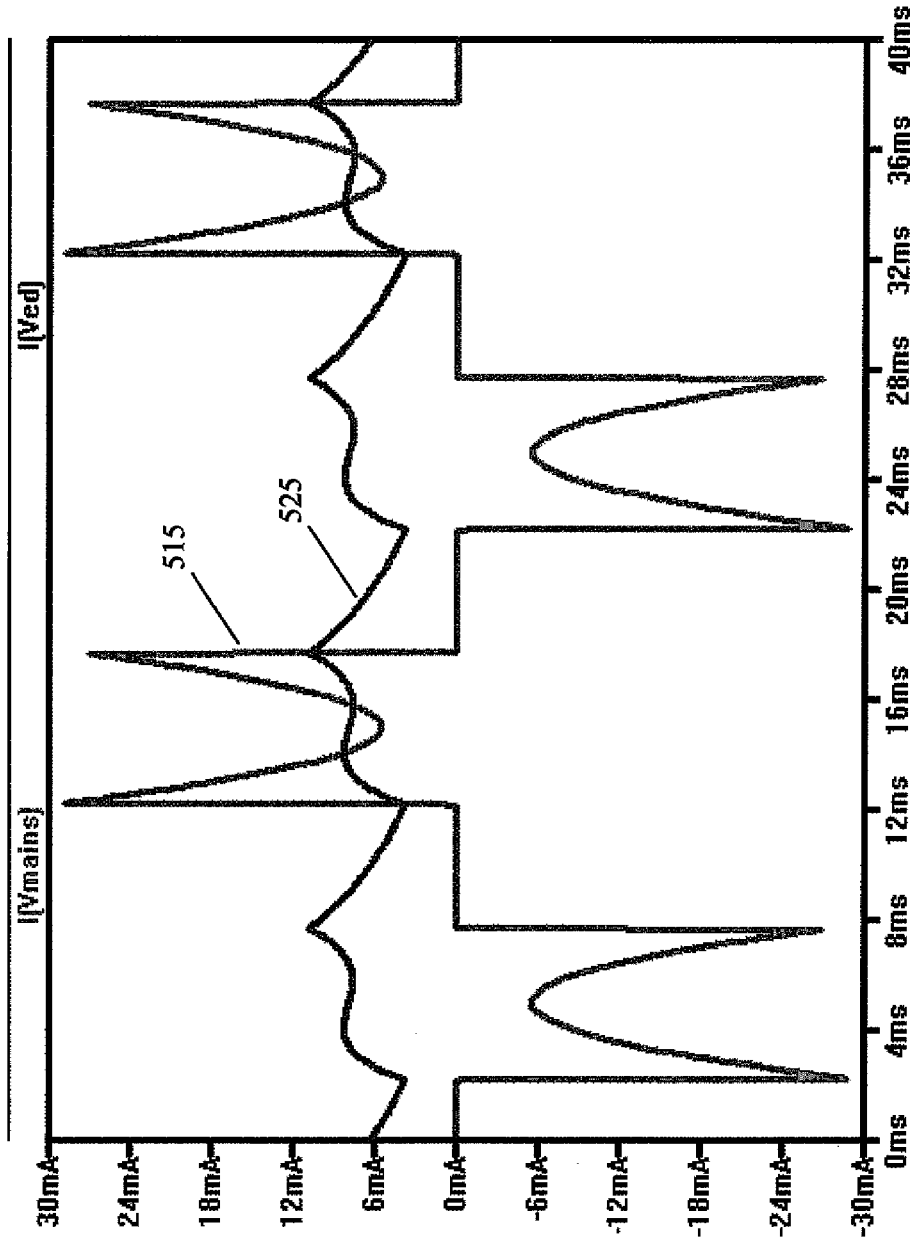

I[Vmains]
I[Ved]
515
525
30mA
24mA
18mA
12mA
6mA
0mA
-6mA
-12mA
-18mA
-24mA
-30mA
0ms
4ms
8ms
12ms
16ms
20ms
24ms
28ms
32ms
36ms
40ms

FIG. 5

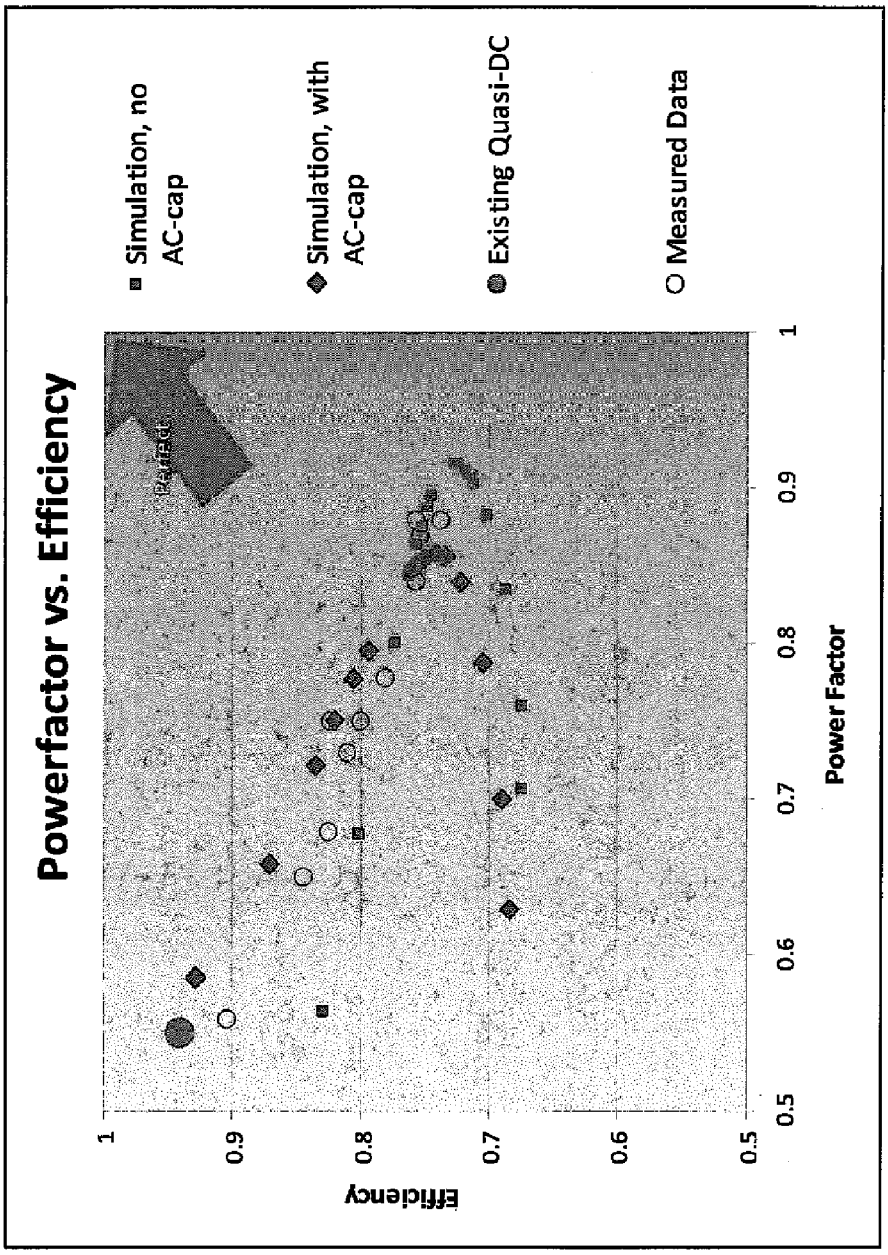

Powerfactor vs. Efficiency
Simulation, no AC-cap
Simulation, with AC-cap
Existing Quasi-DC
Measured Data
Pareto
Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.5
0.6
0.7
0.8
0.9
1
Power Factor

FIG. 6

DEVICE AND METHOD FOR CONTROLLING CURRENT TO SOLID STATE LIGHTING CIRCUIT

TECHNICAL FIELD

The present invention is directed generally to control of solid state lighting devices. More particularly, various inventive methods and apparatus disclosed herein relate to controlling power factor and efficiency of solid state lighting device driver.

BACKGROUND

Digital lighting technologies, i.e. illumination based on semiconductor light sources, such as light-emitting diodes (LEDs), offer a viable alternative to traditional fluorescent, HID, and incandescent lamps. Functional advantages and benefits of LEDs include high energy conversion and optical efficiency, durability, lower operating costs, and many others. Recent advances in LED technology have provided efficient and robust full-spectrum lighting sources that enable a variety of lighting effects in many applications. Some of the fixtures embodying these sources feature a lighting module, including one or more LEDs capable of producing different colors, e.g., red, green and blue, as well as a processor for independently controlling the output of the LEDs in order to generate a variety of colors and color-changing lighting effects, for example, as discussed in detail in U.S. Pat. Nos. 6,016,038 and 6,211,626.

Typically, an LED-based lighting unit or LED load that includes multiple LED-based light sources, such as a string of LEDs connected in series, is driven by a power converter, which receives voltage and current from mains power supply. To reduce driver cost, the LED load may be driven directly from the mains power supply, as an alternative, including AC and DC operation. However, there are drawbacks related to AC driving directly from the mains power supply. For example, the current waveform provided to the LED load has a high peak value compared to the average value. Therefore, the LED load is driven with a reduced efficiency due to droop, as well as a low power factor. Also, current flow is only possible when the instantaneous mains voltage is higher than the forward voltage of the LED load. Therefore, there may be relatively long periods during which no current flows to the LED string and no light is produced, causing flicker.

To partially address these issues, a rectifier circuit may be connected between the mains power supply and the lighting unit, and a capacitor may be connected in parallel with the LED load within the lighting unit. For example, FIG. **1** illustrates a circuit diagram of a conventional LED-based lighting unit **100**, which includes bridge rectifier circuit **110**, LED load **160** and capacitor **141**, which acts as a power factor control (PFC) and smoothing circuit **140**. The capacitor **141** is connected in parallel with the LED load **160**, which includes resistor **163** connected in series with a string of one or more LED light sources, indicated by LEDs **161** and **162**. The bridge rectifier circuit **110** is connected to mains power source **101** via resistor **105**, and includes diodes **111** to **114**. The bridge rectifier circuit **110** thus outputs a rectified mains voltage or input voltage Urect to the circuit **140**.

However, due to the charging and discharging waveform of capacitor current I_C input to the capacitor **141** and the shape of the mains voltage waveform, the LED-based lighting unit **100** typically consumes current, e.g., to recharge the capacitor **141**, within a relatively short time period, resulting in high current peaks and a low power factor. In addition, predominantly the resistor **105** connected to the mains power source **101** limits both the repetitive and the initial charging of the capacitor **141**. Therefore, when the LED load **160** is initially turned on, there may be an excessive in-rush current. For example, if the LED load **160** is turned on during a mains voltage peak of the mains power source **101**, the capacitor current I_C of the capacitor **141** may be relatively large, as compared to nominal operation. As a result, unless LED load **160** includes several light sources connected to one circuit in series, resulting in a relatively low value of the nominal LED operation current, due to the further components in the LED-based lighting unit **100**, already a relatively small number of light sources will be enough to trigger a magnetic release of the circuit breaker. Therefore, the number of LED-based lighting units **100** connectable to one circuit may be dramatically lower (e.g. only 1/10 or even 1/50) than one may expect according to the nominal current.

From efficiency point of view, and when looking at an individual LED-based light source, the waveform of the current does not present a problem. However, when locking at a large number of LED-based light sources, high currents during a short time interval create distortion on the mains grid and may trigger a circuit breaker (e.g., trigger a fast acting magnetic release of a circuit breaker). Due to the mains distortion, use of LED loads with very low power factors is prohibited by regulation. For example, in Europe, the required power factor may be as low as 0.5, which is attainable using the rectifier and capacitor solution, described above. However, other regions require relatively high power factors, such as 0.7 or higher, e.g. 0.9.

Thus, there is a need in the art to AC drive LED-based lighting units directly from the mains power supply, while maintaining relatively high power factors. In addition, there is a need in the art for preventing excessive in-rush currents when initially turning on LED-based lighting units driven directly from the mains power supply.

SUMMARY

The present disclosure is directed to inventive devises and methods for using a dynamically modulated current source in series with a capacitor in an LED lighting unit to shape the capacitor current, thus improving the power factor of the LED lighting unit, while increasing or maximizing efficiency, as well as reducing a peak power dissipation in the current source. Further, the modulated current source limits the input current, preventing the LED lighting unit from triggering a circuit breaker.

Generally, in one aspect, a device is provided for controlling current to a solid state lighting load, the device including a capacitor and a current source. The capacitor is connected in a parallel arrangement with the solid state lighting load. The current source is connected in series with the parallel arrangement of the capacitor and the solid state lighting load, the current source being configured to modulate dynamically an amplitude of an input current provided to the parallel arrangement of the capacitor and the solid state lighting load based on an input voltage.

In another aspect, a device is provided for controlling current to a light emitting diode (LED) load, the device including a capacitor, a transistor and a modulation control circuit. The capacitor is connected in parallel with the LED load. The transistor is connected in series between the capacitor and a bridge rectifier circuit providing a rectified input voltage. The modulation control circuit is connected in parallel with the capacitor and the transistor, and configured to receive the rectified input voltage from the bridge rectifier circuit. The

modulation control circuit includes a current mirror connected to a gate of the transistor, the current mirror being selectively activated and deactivated to downward and upward modulate an amplitude of a current through the capacitor based on an input voltage from the bridge rectifier circuit.

In another aspect, a method is provided for controlling current to a solid state lighting load. The method includes receiving an input voltage having a waveform, and adjusting an amplitude modulation of a capacitor current of a capacitor connected in parallel with the solid state lighting load, in response to at least one of the waveform of the received input voltage and a time delay in the waveform of the received input voltage. Adjusting the amplitude modulation of the capacitor current changes at least one of a power factor and operation efficiency of the solid state lighting load.

As used herein for purposes of the present disclosure, the term "LED" should be understood to include any electroluminescent diode or other type of carrier injection/junction-based system that is capable of generating radiation in response to an electric signal. Thus, the term LED includes, but is not limited to, various semiconductor-based structures that emit light in response to current, light emitting polymers, organic light emitting diodes (OLEDs), electroluminescent strips, and the like. In particular, the term LED refers to light emitting diodes of all types (including semi-conductor and organic light emitting diodes) that may be configured to generate radiation in one or more of the infrared spectrum, ultraviolet spectrum, and various portions of the visible spectrum (generally including radiation wavelengths from approximately 400 nanometers to approximately 700 nanometers). Some examples of LEDs include, but are not limited to, various types of infrared LEDs, ultraviolet LEDs, red LEDs, blue LEDs, green LEDs, yellow LEDs, amber LEDs, orange LEDs, and white LEDs (discussed further below). It also should be appreciated that LEDs may be configured and/or controlled to generate radiation having various bandwidths (e.g., full widths at half maximum, or FWHM) for a given spectrum (e.g., narrow bandwidth, broad bandwidth), and a variety of dominant wavelengths within a given general color categorization.

For example, one implementation of an LED configured to generate essentially white light (e.g., a white LED) may include a number of dies which respectively emit different spectra of electroluminescence that, in combination, mix to form essentially white light. In another implementation, a white light LED may be associated with a phosphor material that converts electroluminescence having a first spectrum to a different second spectrum. In one example of this implementation, electroluminescence having a relatively short wavelength and narrow bandwidth spectrum "pumps" the phosphor material, which in turn radiates longer wavelength radiation having a somewhat broader spectrum.

It should also be understood that the term LED does not limit the physical and/or electrical package type of an LED. For example, as discussed above, an LED may refer to a single light emitting device having multiple dies that are configured to respectively emit different spectra of radiation (e.g., that may or may not be individually controllable). Also, an LED may be associated with a phosphor that is considered as an integral part of the LED (e.g., some types of white LEDs). In general, the term LED may refer to packaged LEDs, non-packaged LEDs, surface mount LEDs, chip-on-board LEDs, T-package mount LEDs, radial package LEDs, power package LEDs, LEDs including some type of encasement and/or optical element (e.g., a diffusing lens), etc.

The term "light source" should be understood to refer to any one or more of a variety of radiation sources, including, but not limited to, LED-based sources (including one or more LEDs as defined above), incandescent sources (e.g., filament lamps, halogen lamps), fluorescent sources, phosphorescent sources, high-intensity discharge sources (e.g., sodium vapor, mercury vapor, and metal halide lamps), lasers, other types of electroluminescent sources, pyro-luminescent sources (e.g., flames), candle-luminescent sources (e.g., gas mantles, carbon arc radiation sources), photo-luminescent sources (e.g., gaseous discharge sources), cathode luminescent sources using electronic satiation, galvano-luminescent sources, crystallo-luminescent sources, kine-luminescent sources, thermo-luminescent sources, triboluminescent sources, sonoluminescent sources, radioluminescent sources, and luminescent polymers.

A given light source may be configured to generate electromagnetic radiation within the visible spectrum, outside the visible spectrum, or a combination of both. Hence, the terms "light" and "radiation" are used interchangeably herein. Additionally, a light source may include as an integral component one or more filters (e.g., color filters), lenses, or other optical components. Also, it should be understood that light sources may be configured for a variety of applications, including, but not limited to, indication, display, and/or illumination. An "illumination source" is a light source that is particularly configured to generate radiation having a sufficient intensity to effectively illuminate an interior or exterior space. In this context, "sufficient intensity" refers to sufficient radiant power in the visible spectrum generated in the space or environment (the unit "lumens" often is employed to represent the total light output from a light source in all directions, in terms of radiant power or "luminous flux") to provide ambient illumination (i.e., light that may be perceived indirectly and that may be, for example, reflected off of one or more of a variety of intervening surfaces before being perceived in whole or in part).

The term "spectrum" should be understood to refer to any one or more frequencies (or wavelengths) of radiation produced by one or more light sources. Accordingly, the term "spectrum" refers to frequencies (or wavelengths) not only in the visible range, but also frequencies (or wavelengths) in the infrared, ultraviolet, and other areas of the overall electromagnetic spectrum. Also, a given spectrum may have a relatively narrow bandwidth (e.g., a FWHM having essentially few frequency or wavelength components) or a relatively wide bandwidth (several frequency or wavelength components having various relative strengths). It should also be appreciated that a given spectrum may be the result of a mixing of two or more other spectra (e.g., mixing radiation respectively emitted from multiple light sources).

The term "lighting fixture" is used herein to refer to an implementation or arrangement of one or more lighting units in a particular form factor, assembly, or package. The term "lighting unit" is used herein to refer to an apparatus including one or more light sources of same or different types. A given lighting unit may have any one of a variety of mounting arrangements for the light source(s), enclosure/housing arrangements and shapes, and/or electrical and mechanical connection configurations. Additionally, a given lighting unit optionally may be associated with (e.g., include, be coupled to and/or packaged together with) various other components (e.g., control circuitry) relating to the operation of the light source(s). An "LED-based lighting unit" refers to a lighting unit that includes one or more LED-based light sources as discussed above, alone or in combination with other non LED-based light sources. A "multi-channel" lighting unit

refers to an LED-based or non LED-based lighting unit that includes at least two light sources configured to respectively generate different spectrums of radiation, wherein each different source spectrum may be referred to as a "channel" of the multi-channel lighting unit.

The term "controller" is used herein generally to describe various apparatus relating to the operation of one or more light sources. A controller can be implemented in numerous ways (e.g., such as with dedicated hardware) to perform various functions discussed herein. A "processor" is one example of a controller which employs one or more microprocessors that may be programmed using software (e.g., microcode) to perform various functions discussed herein. A controller may be implemented with or without employing a processor, and also may be implemented as a combination of dedicated hardware to perform some functions and a processor (e.g., one or more programmed microprocessors and associated circuitry) to perform other functions. Examples of controller components that may be employed in various embodiments of the present disclosure include, but are not limited to, conventional microprocessors, application specific integrated circuits (ASICs), and field-programmable gate arrays (FPGAs).

In various implementations, a processor or controller may be associated with one or more storage media (generically referred to herein as "memory," e.g., volatile and non-volatile computer memory such as RAM, PROM, EPROM, and EEPROM, floppy disks, compact disks, optical disks, magnetic tape, etc.). In some implementations, the storage media may be encoded with one or more programs that, when executed on one or more processors and/or controllers, perform at least some of the functions discussed herein. Various storage media may be fixed within a processor or controller or may be transportable, such that the one or more programs stored thereon can be loaded into a processor or controller so as to implement various aspects of the present invention discussed herein. The terms "program" or "computer program" are used herein in a generic sense to refer to any type of computer code (e.g., software or microcode) that can be employed to program one or more processors or controllers.

The term "addressable" is used herein to refer to a device (e.g., a light source in general, a lighting unit or fixture, a controller or processor associated with one or more light sources or lighting units, other non-lighting related devices, etc.) that is configured to receive information (e.g., data) intended for multiple devices, including itself, and to selectively respond to particular information intended for it. The term "addressable" often is used in connection with a networked environment (or a "network," discussed further below), in which multiple devices are coupled together via some communications medium or media.

In one network implementation, one or more devices coupled to a network may serve as a controller for one or more other devices coupled to the network (e.g., in a master/slave relationship). In another implementation, a networked environment may include one or more dedicated controllers that are configured to control one or more of the devices coupled to the network. Generally, multiple devices coupled to the network each may have access to data that is present on the communications medium or media; however, a given device may be "addressable" in that it is configured to selectively exchange data with (i.e., receive data from and/or transmit data to) the network, based, for example, on one or more particular identifiers (e.g., "addresses") assigned to it.

The term "network" as used herein refers to any interconnection of two or more devices (including controllers or processors) that facilitates the transport of information (e.g. for device control, data storage, data exchange, etc.) between any two or more devices and/or among multiple devices coupled to the network. As should be readily appreciated, various implementations of networks suitable for interconnecting multiple devices may include any of a variety of network topologies and employ any of a variety of communication protocols. Additionally, in various networks according to the present disclosure, any one connection between two devices may represent a dedicated connection between the two systems, or alternatively a non-dedicated connection. In addition to carrying information intended for the two devices, such a non-dedicated connection may carry information not necessarily intended for either of the two devices (e.g., an open network connection). Furthermore, it should be readily appreciated that various networks of devices as discussed herein may employ one or more wireless, wire/cable, and/or fiber optic links to facilitate information transport throughout the network.

The term "user interface" as used herein refers to an interface between a human user or operator and one or more devices that enables communication between the user and the device(s). Examples of user interfaces that may be employed in various implementations of the present disclosure include, but are not limited to, switches, potentiometers, buttons, dials, sliders, a mouse, keyboard, keypad, various types of game controllers (e.g., joysticks), track balls, display screens, various types of graphical user interfaces (GUIs), touch screens, microphones and other types of sensors that may receive some form of human-generated stimulus and generate a signal in response thereto.

It should be appreciated that all combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are contemplated as being part of the inventive subject matter disclosed herein. In particular, all combinations of claimed subject matter appearing at the end of this disclosure are contemplated as being part of the inventive subject matter disclosed herein. It should also be appreciated that terminology explicitly employed herein that also may appear in any disclosure incorporated by reference should be accorded a meaning most consistent with the particular concepts disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, like reference characters generally refer to the same parts throughout the different views. Also, the drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention.

FIG. **1** illustrates a circuit diagram of a conventional device for controlling current to an LED circuit.

FIG. **2** illustrates a circuit diagram of a device for controlling current to an LED circuit, according to a representative embodiment.

FIG. **3** illustrates a circuit diagram of a device for controlling current to an LED circuit, according to a representative embodiment.

FIG. **4** illustrates a circuit diagram of a device for controlling current to an LED circuit, according to a representative embodiment.

FIG. **5** illustrates traces of input current and LED current waveforms provided by a device for controlling current to an LED circuit, according to a representative embodiment.

FIG. **6** is a graph showing simulated performance of a device for controlling current to an LED circuit, according to a representative embodiment.

DETAILED DESCRIPTION

More generally, Applicants have recognized and appreciated that it would be beneficial to maintain high power factors and efficiency while driving LED-based lighting units directly from the mains power supply. Applicants have further recognized and appreciated that it would be beneficial to prevent excessive in-rush currents when initially turning on LED-based lighting units driven directly from the mains power supply.

In view of the foregoing, various embodiments and implementations of the present invention are directed to a driver for an LED-based lighting unit that performs active input current shaping. That is, the driver includes a current source configured to modulate dynamically an amplitude of an input current in response to a waveform of the input voltage, although other input criteria may be used. For example, the amplitude of the input current may be modulated in response to time delay or a combination of time delay and waveform of the input voltage, without departing from the scope of the present teachings. Accordingly, the current of a capacitor connected in parallel with the LED-based lighting unit is actively controlled and shaped towards a time-dependent or state-dependent value. By application of a different shaped current waveform (e.g., having different amplitudes), the power factor and electrical efficiency of the LED-based lighting unit is influenced, so that the LED light sources can be "tuned" to a desired power factor, while maintaining high efficiency. Also, peak power dissipation in the current source may be reduced. The driver may be used, for example, in low wattage LED retrofit lamps and modules with higher power factors.

FIG. **2** illustrates a circuit diagram of a device for controlling current to a solid state lighting load, such as an LED circuit, according to a representative embodiment.

Referring to FIG. **2**, LED-based lighting unit **200** includes bridge rectifier circuit **210**, PFC and smooth circuit **240**, and LED load **260**. The bridge rectifier circuit **210** is connected to mains power source **201** via resistor **205**, and includes diodes **211** to **214**. The bridge rectifier circuit **210** thus outputs a rectified mains voltage Urect to the PFC and smoothing circuit **240**. Some implementations of the LED-based lighting unit **200** may include additional components, as well, as would be apparent to one of ordinary skill in the art. For example, to comply with certain mains distortion regulations, circuitry against over-voltage may be present, such as fuses, noise filtering capacitors, thermal protection means, communication interfaces, and the like. However, these additional components will not be described in detail for clarity of illustration.

The PFC and smoothing circuit **240** includes current source **245**, capacitor **241** and diode **242**. The current source **245** is connected in series between a positive output of the bridge rectifier circuit **210** and node N**1** to receive rectified input voltage Urect and to output capacitor current I_C. The diode **242** is connected in parallel with the current source **245** between the positive output of the bridge rectifier circuit **210** and node N**1**. The diode **242** may be a Zener diode, for example, and is incorporated for surge protection of the current source **245**. For example, without the diode **242**, a large voltage spike (e.g., several times higher than the normal rectified mains voltage Urect) would cause a large voltage across the current source **245**. As a practical matter, the components of the current source **245** (examples of which are discussed below with reference to FIG. **4**) have limited voltage ratings, and thus the diode **242** is selected such that the voltage ratings of these components are not exceeded. In an embodiment, the diode **242** will not carry the surge current, but will overdrive the modulation of the current source **245** to actively clamp the input voltage Urect. In this situation, mainly the resistor **205** provides input current limiting.

The capacitor **241** is connected in series between node N**1** and ground, and thus is separated from the output of the rectifier circuit **210** by the current source **245**. The capacitor **241** is also connected in parallel with LED load **260**, which includes resistor **263** a string of one or more LED light sources, indicated by representative LEDs **261** and **262**. The LED load **260** is connected between node N**1** and ground, and thus is connected in parallel with the capacitor **241**. In the depicted configuration, the resistor **205** and the current source **245** determine the magnitude of the input current I_{In} drawn from the mains power source **201**, which provides capacitor current I_C (i.e., capacitor charging current and capacitor discharging current) through the capacitor **241** and LED current I_{LED} through the LED load **260**, respectively.

The active influence of the current source **245** on the capacitor current I_C enables shaping of the capacitor current I_C, and hence setting the power factor of the PFC and smoothing circuit **240**. The capacitor current I_C is not fixed, but varies dynamically over time and/or state. Indeed, some time component may be involved due to the integrating behavior of the capacitor **241**. In this example, the capacitor current I_C varies in accordance with the waveform of the input voltage Urect from the mains power source **201** and the bridge rectifier circuit **210**, although it is understood that the capacitor current I_C may alternatively vary in accordance with other and/or additional criteria, such as time delay, as mentioned above. For example, the instantaneous value of the input voltage Urect is measured and used as a control signal for the current source **245**. In response to the waveform of the input voltage Urect, the current source **245** modulates the amplitude of the input current I_{In}, resulting in a corresponding modulation in the amplitude of the current given to the parallel arrangement of the capacitor **141** and LED load **260**, indicated as the capacitor current I_C and the LED current I_{LED}, respectively. In a simple case, the amplitude of the input current I_{In} (starting from a predetermined level) is modulated upward (increased) or modulated downward (decreased) in response to increases and decreases in the instantaneous input voltage Urect, respectively. Assuming a relatively stable value of the LED current I_{LED}, this modulation can be found to a large extent as modulation of the capacitor current I_C.

In addition, an in-rush LED current I_{LED} to the LED load **260**, i.e., when the LED load **260** is initially connected to the mains power source **201** after having been turned off, is effectively limited. That is, even during start-up, the LED current I_{LED} is limited to the nominal value, completely omitting the inrush effect. This active current limiting function results from the LED load **260** being connected in parallel to the capacitor **241**. First, the input current I_{IN} to the parallel arrangement of the capacitor **241** and the LED load **260** is limited, and second, the capacitor **241** acts as a higher frequency component bypass for the LED load **260**. Hence, the LED load **260** is effectively protected against inrush current. Also, limiting the input current I_{IN} prevents triggering circuit breakers, as mentioned above.

FIG. **3** illustrates a circuit diagram of a device for controlling current to a solid state lighting load, such as an LED circuit, according to a representative embodiment.

Referring to FIG. **3**, LED-based lighting unit **300** includes bridge rectifier circuit **310**, PFC and smoothing circuit **340** and LED load **360**, which are similar to the bridge rectifier circuit **210**, the PFC and smoothing circuit **240** and the LED load **260** discussed above with reference to LED-based lighting unit **200**. However, the PFC and smoothing circuit **340** in

FIG. **3** includes current source **345**, capacitor **341** and diode **342**, where the current source **345** is connected to the negative output of the bridge rectifier circuit **310**. The current source **345** is connected in series between node N2 and ground, and controls modulation of capacitor current I_C of the capacitor **341** and LED current I_{LED} in response to the waveform of the input voltage Urect, as discussed above. Otherwise, the configuration and operation of the LED-based lighting unit **300** is substantially the same as discussed above with reference to the LED-based lighting unit **200**. The diode **342** is connected in parallel with the current source **345** between the ground output of the bridge rectifier circuit **310** and node N2. As discussed above, the diode **342** may be a Zener diode, for example, and is incorporated for surge protection of the current source **345** and the LED load **360**.

FIG. **4** illustrates a circuit diagram of a device for controlling current to a solid state lighting load, such as an LED circuit, according to a representative embodiment. More particularly, FIG. **4** shows an illustrative implementation of a PFC and smoothing circuit, indicated as PFC and smoothing circuit **440**, according to a representative embodiment.

Referring to FIG. **4**, LED-based lighting unit **400** includes bridge rectifier circuit **410**, PFC and smoothing circuit **440** and LED load **460**. The bridge rectifier circuit **410** is connected to mains power source **401** via resistor **505**, and includes diodes **411** to **414**. The bridge rectifier circuit **410** thus outputs a rectified mains voltage Urect to the PFC and smoothing circuit **440**. In addition, FIG. **4** incorporates (optional) AC capacitors **406** and **407**, to indicate the possibility of altering the input stage. Although two representative capacitors **406** and **407** are depicted, it is understood that one or more capacitors may be present. When no input stage capacitors are used, the input mains current is directly fed to the bridge rectifier **410**, as indicated by jumper X**3**.

The PFC and smoothing circuit **440** includes current source **445** and capacitor **441**, where the current source **445** is connected to the negative output of the bridge rectifier circuit **410**, as discussed above with reference to the current source **345** shown in FIG. **3**. However, it is understood that the current source **445** of FIG. **4** may alternatively be connected to the positive output of the bridge rectifier circuit **410**, as discussed above with reference to the current source **245** shown in FIG. **2**, without departing from the scope of the present teachings. The capacitor **441** is connected in parallel with the LED load **460**, which includes resistor **463** and representative LED load voltage source **461** connected in series.

The current source **445** of the PFC and smoothing circuit **440** includes current source circuit **471** and base level circuit **472**. The current source circuit **471** modulates the input current I_{In}, and includes switch or transistor **442** connected in series between the capacitor **441** and ground. The transistor **442** is depicted as a metal oxide semiconductor field effect transistor (MOSFET), although other types of transistors, such as a bipolar junction transistor (BJT), may be incorporated without departing from the scope of the present teachings. The current source circuit **471** also includes resistor **458**, diode **448** and capacitor **449**, discussed below. The base level circuit **472** determines the nominal, un-modulated input control signal to the current source circuit **471**, and includes resistors **446** and **447**, and diode **457**, which may be a Zener diode, for example.

Generally, the resistor **446** and the diode **457** generate a reference voltage, which is set via the resistor **447** the input control signal of the current source circuit **471**. In particular, the input control signal is gated to the transistor **442** and modulation control circuit **450**, which includes current mirror **459** that is selectively activated in response to operation of jumper X**1**. That is, when the jumper X**1** is closed and the jumper X**2** is opened, the current mirror **459** is activated resulting in downward modulation (lower amplitude) of the input current I_{In}. When the jumper X**2** is closed and the jumper X**1** is opened, the current mirror **459** is deactivated and a current I_{mr} will result in upward modulation (higher amplitude) of the input current I_{Ub}.

More particularly, the modulation control circuit **450** includes resistor **453** and diode **456**, which may be a Zener diode, connected in series between the positive output of the bridge rectifier circuit **410** (for receiving input voltage Urect) and node N**1**. Node N**1** is connected to ground through first and second paths. The first path includes resistor **454** selectively connected in series with transistor **451** of the current mirror **459** via first jumper X**1**. The second path includes resistor **455** selectively connected in series with transistor **452** of the current mirror **459** via first jumper X**2**. The transistors **451** and **452** are depicted as BJTs for purposes of explanation, but may be any of various types of transistors, including field effect transistors (FETs), for example, without departing form the scope of the present teachings. The transistor **451** has a collector connected to the first jumper X**1**, an emitter connected to ground, and a base connected to the collector of the transistor **451** and to a base of the transistor **452**. The transistor **452** has a collector connected to the second jumper X**2**, an emitter connected to ground, and a base connected the base and the collector of the transistor **451**.

With respect to the transistor **442** of the current source circuit **471**, the gate is connected to node N**2**, which is the collector of the transistor **452**. The transistor **442** further includes a drain connected to the capacitor **441** though diode **444**, and a source connected to ground through current shunt resistor **458**, which provides a current shunt resistance. Capacitor **449** and diode **448**, which may be Zener diode, are connected in parallel with one another between the gate and source of the transistor **452**. In addition, resistor **446** is connected between diode **444** and node N**3**. Resistor **447** is connected between nodes N**3** and N**4**, which is the gate of the transistor **442**. Diode **457**, which may be a Zener diode, is connected between node N**3** and ground. Notably, the PFC and smoothing circuit **440** may also include a surge protection diode, such as diode **342** in FIG. **3**, which may be connected in parallel with the transistor **442**, in parallel with the series connection of the transistor **442** and the resistor **458**, in parallel with the resistor **446**, or in any other configuration suitable for limiting voltage across the transistor **442**. However, for clarity of illustration, the surge protection diode is not shown in FIG. **4**.

In the depicted illustrative configuration, the gate voltage of the transistor **442**, the gate-source-voltage U_{GS_442} of the transistor **442**, and the resistor **458** determine the upper limit of the current through the transistor **442**, and thus the upper limit of the input current I_{In} in normal operation, i.e. when over-voltage protections are not active. The gate voltage U_{G_442} of the transistor **442** is normally delivered via the diode **457** and the resistors **446** and **447**. Since the gate of the transistor **442** is decoupled to some extent from the voltage of the diode **457** via the resistor **447**, it is possible to manipulate the gate voltage U_{G_442} and thus the input current I_{In}. The input current I_{In} is modulated upward or downward a certain amount when the input voltage Urect exceeds a voltage threshold defined by diode **456**. Once the voltage threshold has been exceeded, downward modulation is performed via the resistor **454** and the activated current mirror **459** by closing X**1**, and/or upward modulation is performed via resistor **455** by closing the second jumper X**2**.

In various embodiments, there may be active control of the functionality, indicated in FIG. **4** by representative jumpers X**1** and X**2**. For example, the jumpers X**1** and X**2** may be replaced with controllable switches or by other means for activating and deactivating the left and right current paths, respectively, without departing form the scope of the present teachings. The state (e.g., level of the input voltage Urect) at which any of the upward and/or downward modulations is activated may then be selected by additional circuitry (not shown), such as a microprocessor, a processor or a controller.

FIG. **4** depicts a versatile implementation, in which both upward and downward modulations are possible in order to provide maximum flexibility. Of course, alternative implementations enabling only upward or downward modulation may be provided without departing from the scope of the present teachings. For example, a dedicated embodiment, e.g., addressing a certain market with known mains harmonics regulation, may only need to provide upward modulation to achieve the desired combination of efficiency, power factor and mains harmonics. In such a case, there would be no need for the current mirror **459**, for example.

In case more flexibility is required, instead of deriving the upward and downward modulation signal from a common voltage signal generated at node N**1**, one or more zener diodes (not shown) may be added, e.g., in parallel with diode **456**, so that the level of the input voltage Urect at which up modulation begins is different from the level of the input voltage Urect at which down modulation begins. As a result, the input control signal for the current source circuit **471** may be the base reference signal from the base level circuit **472**, as long as the input voltage Urect is lower than either threshold. The input control signal is modulated upward when the input voltage Urect is higher than a first threshold, but lower than a second threshold, and modulated downward when the input voltage Urect is higher than a second threshold. In this configuration, the first and second threshold levels have to be set accordingly (e.g., by choosing the appropriate diodes), and the "strength" of the modulation signal is determined by the values of the resistors **454**, **455** and **447** involved in up and down modulation, which may vary to provide unique benefits for any particular situation or to meet application specific design requirements of various implementations, as would be apparent to one skilled in the art.

In the disclosed embodiments, the current mirror has a ratio of 1:1 between collector current of the transistors **451** and **452**. Some energy associated with generating the collector current from the input voltage can be saved when using a current mirror with a different ration, e.g. by using more transistors or other circuitry.

Referring again to FIG. **4**, as an example operation of the LED-based lighting unit **400**, it may be assumed that the jumper X**1** is closed and the jumper X**2** is open, enabling downward modulation of the amplitude of the input current I_{In}. In particular, the default programmed current I_0 is indicated by Equation (1), where U_{457} is the voltage across the diode **457**, U_{GS_442} is the gate-source-voltage of the transistor **442**, and R_{458} is the resistance of the resistor **458**:

$$I_0 = \frac{U_{457} - U_{GS\_442}}{R_{458}} \tag{1}$$

On the left side of the current mirror **459**, current I_{ml} of the transistor **451** of the current mirror **459** is indicated by Equation (2), where U_{456} is the voltage across the diode **456**, U_{BE_452} is the base-emitter voltage of the transistor **452**, R_{453} is the resistance of the resistor **453** and R_{454} is the resistance of the resistor **454**:

$$I_{ml} = \frac{Urect - U_{456} - U_{BE\_452}}{R_{453} + R_{454}} \tag{2}$$

Typically, the 0.7V of U_{BE_452} may be ignored. Due to the configuration of the current mirror **459**, the same value of the current I_{ml} is provided on the right side of the current mirror **459** as current I_{mr}, which is equal to the collector current I_{C_452} at the collector of the transistor **452**. The collector current I_{C_452} is drawn through the decoupling resistor **447**, resulting in a proportional voltage drop. Therefore, the remaining gate voltage U_{G_442} of the transistor **442** is reduced, and thus the remaining input current I_{In} is limited as shown in Equation (3):

$$I_{in} = \frac{U_{457} - U_{GS\_442} - R_{447} \cdot \frac{(Urect - U_{456})}{R_{453} + R_{454}}}{R_{458}} \tag{3}$$

Of course, a similar equation may be derived for the upward modulation when jumper X**1** is opened and jumper X**2** is closed. Also, the values of the various components, the default (maximum) input current In and the degree of downward modulation may vary to provide unique benefits for any particular situation or to meet application specific design requirements of various implementations, as would be apparent to one of ordinary skill in the art. For example, for purposes of illustration, non-limiting values of the various components in FIG. **4** may be as follows: Capacitors **406** and **407** may be 1000 nf and 680 nf, respectively, and the resistor **405** may be 100 Ω. In the PFC and smoothing circuit **440**, the capacitor **441** may be 5 μf, the capacitor **449** may be 1 nf, the resistor **453** may be 200 kΩ, the resistor **446** may be 39 kΩ, and the resistor **447** may be 22 kΩ. Also, the current mirror transistors **451** and **452** may be NPN BJTs, ad the transistor **442** may be an NMOS MOSFET. In various alternative configurations, the transistors **451** and **452** may PNP BJTs and/or their collectors and emitters may be reversed, and the transistor **442** may a PMOS MOSFET and/or its source and drain may be reversed. In the LED load **460**, the resistor may be 470Ω and the LED load voltage source **461** may be a series connection of multiple LED junctions, having a suitable high forward voltage, e.g., around 60 to 130V when operated from a 120V AC grid. The LED load voltage source **461** is included in order to represent the general behavior of an LED load, having a relatively limited input voltage range for operation, e.g., as compared to a resistor. Still, the LED load voltage source **461** will incorporate some resistive behavior. This resistive behavior may be sufficient to realize the functionality depicted by the resistor **463** in FIG. **4**, although it may also be that the functionally depicted by the resistor **463** is realized by the internal resistive behavior of the LED load voltage source **461** and an additional resistance (e.g., resistive trace on a circuit board or a resistor).

As stated above, input criteria other than waveform of the input voltage may be used, such as time delay or a combination of time delay and waveform of the input voltage, without departing from the scope of the present teachings. For example, the current source may be actuated according to a waveform, but with a certain time delay. In a representative configuration, the time delay may be realized via a resistor-

capacitor delay, e.g., including capacitors **406** and **407** in FIG. **4**, or via a real "record and playback" circuit, to capture the waveform of one cycle, shift it in time and use the time shifted signal for modulation in a later part of this cycle or in any subsequent cycle.

FIG. **5** illustrates traces of input current and LED current waveforms provided by a device for controlling current to an LED circuit, according to a representative embodiment.

Referring to FIG. **5**, trace **515** shows a waveform of a representative input current I_{In} and trace **525** shows a resulting waveform of a representative LED current I_{LED}, where the PFC and smoothing circuit **440** provides heavy downward modulation. For example, the trace **525** may result when the jumper X**1** is closed and the jumper X**2** is open, activating the current mirror **459** of the PFC and smoothing circuit **440**. A benefit of downward modulation is that the current is reduced while the voltage difference between the input voltage Urect and the capacitor voltage across the transistor **442** is maximum. This voltage difference is the drop-out voltage across the current source **445**, which to a large extent is the voltage across the transistor **4442**. By reducing the input current I_{In} at this high level of the input voltage Urect, the energy dissipation in the current source **445** is limited, and thus the efficiency is increased. Of course, a certain average input current I_{In} must be delivered to the LED load **460**. The higher input current I_{In} at the lower levels of the input voltage Urect provides more charging current (capacitor current I_C) to the capacitor **441**, to achieve the desired level of average LED current I_{LED} to the LED load **460**. With this downward modulation, efficiency is increased and the peak thermal loading (stress) of the current source **445** is beneficially reduced. In addition, flicker of the LED load **460** is reduced, since the total charging of the capacitor **441** is effectively split into two portions, resulting in a reduced voltage ripple across the capacitor **441** and hence reduced ripple of the LED current I_{LED}. Furthermore, the ripple of the LED current I_{LED} incorporates higher frequency components, where the human eye is less sensitive.

FIG. **6** is a graph showing simulated performance of a device for controlling current to an LED circuit, according to a representative embodiment. In particular, FIG. **6** shows operation points (e.g., including one or more AC side capacitors **460**, **407**) ranging from an efficiency of about 92 percent for a power factor of about 0.58 to an efficiency of about 75 percent for a power factor of about 0.85, indicated by black diamonds. Additional simulations of performance show operation points (e.g., with no AC side capacitors) ranging from an efficiency of about 83 percent for a power factor of about 0.56 to an efficiency of about 72 percent for a power factor of about 0.91, indicated by black squares. For purposes of comparison, FIG. **6** also shows the existing quasi-DC operation point, indicated by a black circle, and measured data, indicated by open circles.

While several inventive embodiments have been described and illustrated herein, those of ordinary skill in the art will readily envision a variety of other means and/or structures for performing the function and/or obtaining the results and/or one or more of the advantages described herein, and each of such variations and/or modifications is deemed to be within the scope of the inventive embodiments described herein. More generally, those skilled in the art will readily appreciate that all parameters, dimensions, materials, and configurations described herein are meant to be exemplary and that the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the inventive teachings is/are used. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific inventive embodiments described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, inventive embodiments may be practiced otherwise than as specifically described and claimed. Inventive embodiments of the present disclosure are directed to each individual feature, system, article, material, kit, and/or method described herein. In addition, any combination of two or more such features, systems, articles, materials, kits, and/or methods, if such features, systems, articles, materials, kits, and/or methods are not mutually inconsistent, is included within the inventive scope of the present disclosure.

All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

The indefinite articles "a" and "an," as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean "at least one."

The phrase "and/or," as used herein in the specification and in the claims, should be understood to mean "either or both" of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with "and/or" should be construed in the same fashion, i.e., "one or more" of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the "and/or" clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to "A and/or B", when used in conjunction with open-ended language such as "comprising" can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

As used herein in the specification and in the claims, "or" should be understood to have the same meaning as "and/or" as defined above. For example, when separating items in a list, "or" or "and/or" shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as "only one of" or "exactly one of," or, when used in the claims, "consisting of," will refer to the inclusion of exactly one element of a number or list of elements. In general, the term "or" as used herein shall only be interpreted as indicating exclusive alternatives (i.e. "one or the other but not both") when preceded by terms of exclusivity, such as "either," "one of," "only one of," or "exactly one of." "Consisting essentially of," when used in the claims, shall have its ordinary meaning as used in the field of patent law.

As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified.

It should also be understood that, unless clearly indicated to the contrary, in any methods claimed herein that include

more than one step or act, the order of the steps or acts of the method is not necessarily limited to the order in which the steps or acts of the method are recited.

Any reference numerals or other characters, appearing between parentheses in the claims, are provided merely for convenience and are not intended to limit the claims in any way.

In the claims, as well as in the specification above, all transitional phrases such as "comprising," "including," "carrying," "having," "containing," "involving," "holding," "composed of," and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases "consisting of" and "consisting essentially of" shall be closed or semi-closed transitional phrases, respectively.

The invention claimed is:

1. A device for controlling current to a solid state lighting load, the device comprising:

a capacitor connected in a parallel arrangement with the solid state lighting load;

a current source connected in series with the parallel arrangement of the capacitor and the solid state lighting load, the current source being configured to modulate dynamically an amplitude of an input current provided to the parallel arrangement of the capacitor and the solid state lighting load based on an input voltage; and

a diode providing surge protection of the current source, connected in parallel with the current source.

2. The device of claim **1**, wherein the solid state lighting load comprises at least one light-emitting diode (LED).

3. The device of claim **2**, wherein the modulated amplitude of the input current maximizes operational efficiency of the solid state lighting load and increases a power factor (PF) of the solid state lighting load to at least a minimum PF requirement.

4. The device of claim **2**, wherein the modulated amplitude of the input current reduces peak power dissipation in the current source.

5. The device of claim **1**, wherein the solid state lighting load comprises at least two light-emitting diodes (LEDs) connected in series with each other.

6. The device of claim **1**, wherein the diode comprises a Zener diode.

7. The device of claim **1**, wherein the current source comprises a metal oxide semiconductor field effect transistor (MOSFET).

8. The device of claim **1**, wherein the current source comprises a bipolar junction transistor (BJT).

9. The device of claim **1**, wherein the input voltage is provided by a rectifier supplied from an AC source.

10. The device of claim **9**, wherein the rectifier is a bridge rectifier and the AC source is a mains voltage source.

11. A device for controlling current to a light emitting diode (LED) load, the device comprising:

a capacitor connected in parallel with the LED load;

a transistor connected in series between the capacitor and a bridge rectifier circuit providing a rectified input voltage; and

a modulation control circuit connected in parallel with the capacitor and the transistor and configured to receive the rectified input voltage from the bridge rectifier circuit, the modulation control circuit comprising a current mirror connected to a gate of the transistor, the current mirror being selectively activated and deactivated to downward and upward modulate an amplitude of a current through the capacitor based on an input voltage from the bridge rectifier circuit.

12. The device of claim **11**, wherein the current mirror comprises a plurality of current mirror transistors.

13. The device of claim **12**, wherein the modulation control circuit comprises:

a first resistor and a diode connected in series between the bridge rectifier circuit and a first node;

a first path connected between the first node and ground, the first path comprising a second resistor and a first one of the current mirror transistors of the current mirror; and

a second path connected between the first node and ground, the second path comprising a third resistor and a second one of the current mirror transistors of the current mirror,

wherein selection of the first path causes downward modulation of the current through the capacitor, and selection of the second path causes upward modulation of the current through the capacitor.

14. The device of claim **13**, wherein the current through the capacitor is further modulated upward or downward when the input voltage exceeds a voltage threshold defined by the diode.

15. The device of claim **11**, wherein the transistor comprises a MOSFET.

16. The device of claim **12**, wherein each of the current mirror transistors comprises a bipolar junction transistor (BJT).

17. The device of claim **11**, wherein the modulation control circuit further comprises a current shunt resistor connected in series between the transistor and ground, a gate-source-voltage of the transistor and the current shunt resistor determining an upper limit of a current through the transistor.

18. The device of claim **11**, further comprising:

at least a second capacitor selectively connectable to the bridge rectifier circuit to alter the input voltage.

19. A method for controlling current to a solid state lighting load, the method comprising:

receiving an input voltage (Urect) having a waveform; and

adjusting an amplitude modulation of a capacitor current of a capacitor connected in parallel with the solid state lighting load and further connected in series with a transistor, in response to at least one of the waveform of the received input voltage and a time delay in the waveform of the received input voltage, by a modulation control circuit comprising a current mirror connected to a gate of the transistor, the current mirror being selectively activated and deactivated to downward and upward modulate an amplitude of the current through the capacitor based on the input voltage, wherein adjusting the amplitude modulation of the capacitor current changes at least one of a power factor and operation efficiency of the solid state lighting load.

20. The method of claim **19**, wherein the input voltage comprises a rectified voltage received from a bridge rectifier circuit.

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