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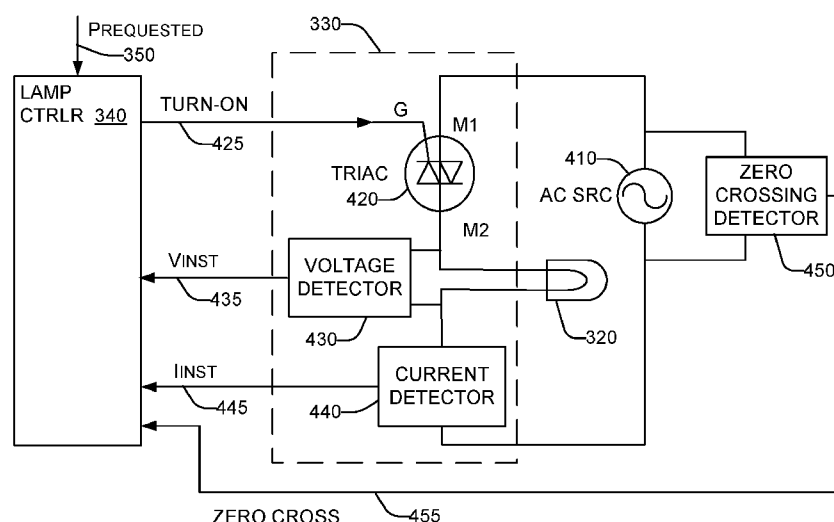
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(54) Title: LAMP AND TRIAC CONTROL

**FIG. 4**

(57) Abstract: In one example, a control system for a lamp. A controller is to compute a turn-on time of a Triac for a next half-cycle of AC using a specified lamp power level and instantaneous voltage and current of the lamp for a present half-cycle, and turn the Triac on at the turn-on time during the next half-cycle.



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LAMP AND TRIAC CONTROL

Background

[0001] Lamps convert electrical energy into light energy and/or heat energy. Additive manufacturing (AM) is a popular technique for fabricating three-dimensional (3D) objects from a build material in a layer-by-layer manner. Some additive manufacturing systems use one or more lamps to selectively provide heat energy to a portion of a layer of build material for the 3D object being fabricated. Precise temperature control of the build material during the fabrication process helps ensure that the 3D object is of high quality, and to achieve an intended temperature level a lamp may be controlled to operate at a particular power level. Some lamps, such as for example incandescent lamps, have a resistance which changes with temperature. This characteristic can make it difficult to precisely control the power level at which the lamp is operated.

Brief Description of the Drawings

[0002] FIG. 1 is a schematic representation of an additive manufacturing system in accordance with an example of the present disclosure.

[0003] FIG. 2 is a schematic representation of a heating lamp array usable with the additive manufacturing system of FIG. 1 in accordance with an example of the present disclosure.

[0004] FIG. 3 is a schematic representation of a lamp control system usable with the heating lamp array of FIG. 2 and the additive manufacturing system of FIG. 1 in accordance with an example of the present disclosure.

[0005] FIG. 4 is a more detailed electrical schematic representation of a portion of the lamp control system of FIG. 3 for a single one of the lamps in accordance with an example of the present disclosure.

[0006] FIG. 5 is a schematic timing diagram of one cycle of an example AC waveform provided to the lamp control system of FIG. 4 in accordance with an example of the present disclosure.

[0007] FIG. 6 is a flowchart in accordance with an example of the present disclosure of a method of operating a Triac-controlled lamp at a specified power level.

[0008] FIG. 7 is another flowchart in accordance with an example of the present disclosure of a method of operating a Triac-controlled lamp at a specified power level.

[0009] FIG. 8 is a schematic representation of a lamp controller usable with the lamp control system of FIG. 3 and the additive manufacturing system of FIG. 1 in accordance with an example of the present disclosure.

Detailed Description

[0010] Some AM systems utilize tungsten, or tungsten-halogen, lamps. These lamps generate light having an adequate wavelength in the infrared (IR) region to serve as a heat source for an AM system, and have a sufficiently fast heat output response to changes in the power level applied to the lamp to allow the temperature within the AM system to be maintained within allowable limits of a desired temperature.

[0011] These lamps have a filament through which current flows. The temperature of the filament increases with increasing current flow. The resistance of the lamp also increases with the temperature of the filament. In some examples, the temperature increases monotonically, but not necessarily linearly, with temperature. In some examples, the resistance of a hot lamp operating at its rated power (i.e. at its full rated voltage and current) is about 15 times greater than the resistance of a cold lamp, due to the difference in filament temperature. As a result, when full power is applied to a cold lamp, the lamp draws a high inrush current for a very short period of time, as the filament quickly heats to its hot temperature. The rated life of the lamp is based on drawing such high currents for short periods of time; operation of the lamp at higher-than-rated current levels for extended periods of time can undesirably reduce the life of the lamp.

[0012] However, to control the temperature within an AM system, it may be desired to operate a lamp for an extended period time at a power level which

is much less than 100% of its rated power, in order to generate a fraction of the full amount of heat energy the lamp can supply. As an example, the desired power level may be 20% of the rated power. At such low power levels, the filament temperature is significantly cooler, and thus the resistance of the lamp is significantly lower than its rated resistance. If a 20% power level were to be implemented by a 20% duty cycle (i.e. by applying the rated voltage to the lamp 20% of the time), high peak currents would occur due to the lower lamp resistance, adversely affecting the reliability and lifetime of the lamp. In addition, it is difficult to accurately achieve a particular level of power if the resistance is unknown due to temperature variation.

[0013] Referring now to the drawings, there is illustrated an example of power control which enables a lamp to operate for an extended period time at a low power level without significant adverse effects on the reliability and lifetime of the lamp. The instantaneous voltage and current of a Triac-controlled lamp is measured while the Triac is conducting (i.e. when the lamp is turned on) during a half-cycle of AC power from a source connected in series with the Triac and the lamp. At the end of the half-cycle, the Triac stops conducting. A turn-on time of the Triac for the next half-cycle of AC power is computed using a specified lamp power level and the instantaneous measured voltage and current. The controller then turns on the Triac at that computed turn-on time.

[0014] Considering now one example additive manufacturing system, and with reference to FIG. 1, an additive manufacturing system 100 includes a build chamber 110 in which at least one 3D object can be fabricated on a build platform 115. The build platform 115 is substantially planar in the X-Y plane (the Y direction is into and out of the page). In one example, the build platform 115 is 12 by 12 inches.

[0015] In some examples, the 3D object is fabricated according to a 3D digital representation (or "model") which is divided ("sliced") into a series of thin, adjacent parallel planar slices, and the 3D object is then fabricated layer-by-layer with each slice of the representation generally corresponding to a layer of the physical object to be fabricated. During fabrication, the first layer

is formed on the build platform 115, and then each next layer is formed on top of the adjacent previous layer(s). In one example, each layer is about 0.1 millimeter in thickness.

[0016] To fabricate each layer of the 3D object, one type of additive manufacturing selectively deposits a fusing agent onto build material, and a heat source then fuses the build material at the locations at which the fusing agent has been deposited. In some examples, the build material is a light color particulate material or powder, which may be white. In one example, the build material is polyamide (nylon). Other build materials may be powders of one or more different materials. In one example, the powder particles range from 5 to 200 microns in size. In one example, the powder particles may have an average size of 50 microns.

[0017] To deposit the fusing agent, a print engine controllably ejects drops of a liquid fusing agent onto the regions of build material which correspond generally to the location of the 3D object's cross-section within the corresponding digital slice. The print engine, in one example, uses inkjet printing technology. In various examples, the fusing agent is a dark colored liquid such as for example black pigmented printing liquid, an IR absorbent liquid or printing liquid, and/or other liquid(s). The heat source then traverses the entire print zone. The regions of the powder onto which the fusing agent has been deposited absorbs sufficient radiated heat energy from the heat source to melt the powder in those regions, fusing that powder together and to fused powder in the previous layer underneath. However, regions of the powder onto which fusing agent has not been deposited do not absorb sufficient radiated heat energy to melt the powder. As a result, those portions of the layer on which no fusing agent was deposited remain in unfused powdered form. To fabricate the next layer of the object, another layer of powdered build material is deposited on top of the layer which has just been processed, and the printing and fusing processes are repeated for the next digital slice. This process continues until the object has been completely fabricated.

[0018] FIG. 1 illustrates the system 100 during an intermediate operation of the fabrication process for the 3D object, where an intermediate layer is being fabricated. A layer 130 of unfused build material has been deposited on top of previous layers 132 in which portions of the build material for the 3D object have already been fused. A volume defined by the dimensions of the build platform 115 in the X and Y directions and the span in the Z direction of the layers 130, 132 constitutes a build bed 120 that serves as the work area for fabrication of the 3D object. In some examples, the build platform 115 moves downward in the Z direction between fabrication of individual layers by a distance substantially equal to the thickness of the layer, making room for the build material used for the next layer 130.

[0019] The system 100 includes two different sources of heat energy: a fusing lamp 140 and a heating lamp array 150. The fusing lamp 140 may be mounted on a movable carriage along with the fusing agent print engine 160, where the carriage traverses the span of the build bed 120 in the X direction during fabrication of a layer. The print engine 160 selectively deposits drops 162 of the fusing agent onto the appropriate X and Y locations of the layer 130 as the carriage traverses the build bed 120. The fusing lamp 140 radiates heat energy 142 onto the layer 130 as the carriage traverses the build bed 120. In one example, the fusing lamp 140 is a single lamp with a rated power of 1500 watts. In one example, the fusing lamp 140 operates at its rated power throughout a fusing operation for a layer. One or both of the print engine 160 and the fusing lamp 140 may operate during a given traversal of the carriage, and the carriage may traverse the build bed 120 one or more times during fabrication of a layer.

[0020] The lamp array 150 is a top bed heating array disposed above the build bed 120, including the top layer 130. In some examples, the lamp array 150 is maintained in a fixed position during fabrication of a 3D object. The lamp array 150 includes a plurality of lamps. The temperature of the build bed 120 can vary across the X and Y directions; for example, the center of the build bed is typically warmer than the edges. This temperature variation is undesirable, particularly in the top layer 130, so one function of the lamp array

150 is to radiate heat energy 152 to warm the entire surface area of the build bed 120 (i.e. the top layer 130) to a substantially uniform temperature and maintain it at this temperature. In some examples, this temperature is slightly below the temperature at which the build material will fuse. In one example, the desired variation in temperature to be achieved in the build bed 120 is less than 4 degrees C between any two points of the bed 120. To achieve and maintain a substantially uniform build bed temperature, the power level of each of the lamps in the lamp array 150 is individually controllable such that different amounts of power may be applied to different ones of the lamps.

[0021] Another function of the lamp array 150 is to assist the fusing lamp 140 in certain situations with fusing the build material. For example, the 3D slice being fabricated may have a higher density of 3D part structure (i.e. build material to be fused) at one side of the build bed in the Y direction than at the other side, and the single fusing lamp 140 may be unable to fully fuse the denser portion of the structure. To compensate, each lamp in the lamp array 150 has a rated full power that is sufficient to assist with fusing the build material when needed. In one example, each of the lamps in the lamp array 150 has a 300 watt to 400 watt full power rating. However, operating these lamps at their full rated power would usually provide too much radiant heat for warming the build bed 120 to eliminate temperature variations, and cycling these lamps between the off and fully on states would result in excessive temperature variations. The most effective warming is achieved by operating the lamps at low power levels for relatively long periods of time, in some cases many minutes or even continuously.

[0022] The system 100 includes a controller 170. The controller 170 is coupled to each of the lamps in the lamp array 150 to operate each lamp at a specified power level for that lamp. In some examples, the controller 170 is also coupled to at least one temperature detector or sensor which measures the temperature of different regions or zones of the build bed 120 and determines the power level to be specified for each lamp. In some examples, the controller 170 also accesses data for the 3D slice and determines the

power level to be specified for each lamp if and when that lamp is to assist with fusing the build material.

[0023] Considering now one example lamp array 150 in greater detail, and with reference to FIG. 2, the lamp array 150 is depicted looking up from the build bed 120 into the lamp array 150. The lamp array 150 includes plural individual lamps 210. The individual lamps 210 may be positioned in the lamp array 150 in locations that can achieve optimal uniform heating of the build bed 120. In some examples all the lamps 210 may have the same rated power, while in other examples the rated power may differ among different lamps 210.

[0024] In some examples, the lamp array 150 is organized into zones 220 (indicated by dashed lines). The lamp array 150 has ten zones 220. Each lamp 210 is associated with a heating zone 220. The number of lamps 210 in a zone 220 may vary, as may the size of a zone 220 in the x-y plane.

[0025] In some examples, a zone 220 corresponds to a region of the build bed 120 in the x-y plane. The AM system 100 includes at least one sensor to detect the temperatures of plural regions of the build bed 120. In some examples, a temperature is measured for each region of the build bed 120, and the measured temperature for a region determines, at least in part, the power level of the lamps 210 in the zone 220 corresponding to that region. The lamps 210 in a zone 220 may be set to the same power level or different power levels.

[0026] Temperature may be measured using at least one temperature detector or sensor which collectively detects the temperature of the plural regions of the build bed. In some examples, a temperature sensor 230, such as for example an infrared camera, may be disposed in the lamp array 200, or at another location in the system 100. In other examples, plural temperature sensors for measuring the temperature at the regions of the build bed 120 corresponding to the zones 220 may be disposed in the build platform 115 or elsewhere in the system 100.

[0027] Considering now the control of a heating lamp array of an additive manufacturing system 300, and with reference to FIG. 3, the system 300

includes a heating lamp array 310. In some examples, the system 300 may be or include the system 100 (FIG. 1) and the heating lamp array 310 may be or include the heating lamp array 150 (FIG. 1). The heating lamp array 310 includes plural lamps 320, each of which may be one of the lamps 210 (FIG. 2).

[0028] As is discussed subsequently in greater detail, each lamp 320 is coupled to a corresponding Triac-based control circuit 330 which controls the voltage applied to, and current flowing through, that lamp 320. Each Triac-based control circuit 330 is in turn coupled to a lamp controller 340 which independently turns on the Triac of each Triac-based control circuit 330 at a specific time during a half-cycle of an AC waveform. In this way, the controller 340 operates the lamp 320 coupled to that Triac-based control circuit 330 at a requested power level 350 for that lamp 320. Each lamp 320 may be operated at a different requested power level 350. In some examples, the requested power level that is specified for a lamp 320 is a percentage from 0% to 100% of a rated full power of the lamp 320.

[0029] The requested power level 350 is determined using temperature data 375 obtained from at least one temperature detector 370. A processor 380 computes the requested power level 350 for each lamp 320 and sends the requested power level to the controller 340. Different ones of the plural regions of the build bed can have different detected temperatures, and the requested power level for each lamp may be chosen to reduce temperature differences among the plural regions.

[0030] In some examples, the requested power level 350 is also determined using 3D object slice information 377 for the layer of the 3D object which is presently being fabricated. The slice information 377 defines which feature(s), if any, of that slice of the 3D object are to be fabricated in a particular region of the build bed. In situations where a lamp 320 of the zone of the heating lamp array which corresponds to that particular region of the build bed is to assist with fusing the build material in that region, the requested power level of that lamp 320 is further chosen to supply a desired amount of fusing heat energy to that region.

[0031] While the processor 380 and controller 340 are illustrated as separate elements in FIG. 3, in other examples they may be combined into a single processor or controller. The controller 170 (FIG. 1) may include the lamp controller 340 and/or the processor 380.

[0032] Considering now the lamp controller 340 in greater detail, and with reference to FIG. 4, the lamp controller 340 is illustrated with a single one of the lamps 320 and Triac-based control circuits 330 of FIG. 3.

[0033] The Triac-based control circuit 330 is electrically coupled to the lamp 320 and an AC (alternating current) power source 410. The Triac-based control circuit 330 includes a Triac 420, a voltage detector 430, and a current detector 440. The circuit 330 connects the AC power source 410, the main terminals M1 and M2 of the Triac 420, the lamp 320, and the current detector 440 in series. The voltage detector 430 is connected in parallel with the lamp 320 to measure the voltage across the lamp 320. The voltage detector 430 and the current detector 440 are also electrically coupled to the lamp controller 340.

[0034] The Triac 420 acts as a switch to control whether, and when, alternating current from the AC power source 410 flows through the lamp to illuminate it and generate heat energy. A turn-on signal 425 received at the gate input G of the Triac 420 will turn on (or "trigger") the Triac 420 and allow it to conduct. This allows the current to flow through the lamp and the current measurement circuit 440. The Triac 420 automatically turns off at the end (zero crossing) of each half-cycle of AC power provided by the AC source 410. In addition, a zero crossing detector 450 connected in parallel with the AC source 410 provides a zero crossing signal 455 to the lamp controller 340 at the end of each half-cycle.

[0035] When the Triac 420 is conducting and the lamp 320 is emitting energy, the voltage detector 430 measures an instantaneous voltage V_{inst} 435 across the lamp 320, and the current detector 440 measures an instantaneous current I_{inst} 445 through the lamp 320. The instantaneous voltage V_{inst} 435 and the instantaneous current I_{inst} 445 are provided to the lamp controller 340. In some examples, the controller 340 triggers the

measurements made by the voltage detector 430 and the current detector 440.

[0036] The lamp controller 340 uses the instantaneous voltage V_{inst} 435 and the instantaneous current i_{inst} 445 measured when the Triac 420 is conducting during a current half-cycle of AC power from the AC source 410, along with the requested power level 350, to compute a turn-on time of the Triac 420 for the next half-cycle. The turn-on time is relative to the start of the next cycle. The lamp controller 340 uses the zero crossing signal 455 to detect the start of the next half-cycle, and then turns on the Triac 420 at the turn-on time during that next half-cycle.

[0037] Through controlling the turn-on time of the Triac 420 in this manner, the lamp controller 340 can maintain the current in the lamp 320 below the lamp's rated full-power current when operating at any value of requested power between 0% and 100%. The rated full-power (100% power) current corresponds to the current through the lamp when the filament is hottest, and thus the lamp resistance highest. However, when the lamp 320 is operated at much lower requested power levels, such as 30% or less, the filament will be cooler, and the lamp resistance lower, which would otherwise lead to currents which exceed the rated full-power value and could reduce the lifetime of the lamp. But the lamp controller 340 allows the lamp 320 to be operated for long periods of time (or even continuously) at low power levels. The computation of the turn-on time to accomplish this is discussed subsequently in greater detail.

[0038] In some examples, the AC source 410 generates a high-quality AC waveform. In other examples, such as for example in some industrial operating environments, the AC source 410 may be of lower quality. In some examples, the AC source 410 may be the AC mains of the facility in which the additive manufacturing system is installed. In some examples, the same AC source 410 is connected in parallel to all the lamps 320. The AC source 410 is of a sufficient power rating to supply current to all of the lamps 320 simultaneously during operation.

[0039] In some examples, the Triac 420 has a rated voltage which is above the AC voltage generated by the AC source 410 and the operating voltage of the lamp 320, and a rated power which is above the rated power of the lamp 320..

[0040] In some examples, the lamp 320 is a tungsten-halogen lamp having a temperature-dependent resistance. Lamps which are suitable to achieve a uniform temperature throughout the build bed emit energy at wavelengths which appropriate for heating the build material, and their energy output responds sufficiently rapidly to changes in the electrical power applied to the lamp. In some examples, the lamp 320 emits energy at wavelengths in the range of 800 to 1200 nanometers, and responds within 10 milliseconds to a change in electrical power of 10%.

[0041] In some examples, the voltage detector 430 is a voltage measurement circuit which is implemented using a 10-bit A/D converter. The voltage detector 430 may be a separate element from the lamp controller 340, or may be implemented in whole or in part within the lamp controller 340.

[0042] In some examples, the current detector 440 is a current measurement circuit which is implemented using a series sense resistor plus a differential voltage measurement circuit. In other examples, a Hall effect sensor and/or a current mirror circuit is used. In some examples, the current detector 440 converts the current value into a proportional voltage which is then measured with a 10-bit A/D converter.

[0043] In some examples, the zero crossing detector 450 is implemented using a Zener diode plus a resistor connected to an interrupt line of the lamp controller 340 such that, when the AC voltage is positive, the interrupt line receives the diode reverse voltage (for example, 5 volts) and when the AC voltage is negative, the microcontroller receives zero volts. The transition from logic '0' to logic '1' (and analogously from logic '1' to logic '0') generates the interrupt signal for a zero crossing event.

[0044] Considering now the operation of the Triac 420 and the lamp 320 of FIG. 4 in response to an AC waveform supplied by the AC source 410, and with reference to FIG. 5, one cycle of an AC waveform 500 is illustrated, with

a first half-cycle N 502 and a second, subsequent half-cycle N+1 504. For a 50 hertz AC waveform, each half cycle 502, 504 is 10 milliseconds.

[0045] As has been described heretofore, the Triac 420 automatically turns off (i.e. stops conducting current) at each zero-crossing point (T0, T2, and T4). The Triac 420 is turned on (i.e. conducts current) by the turn-on signal 425 applied by the lamp controller 340 to the gate input of the Triac 420. Accordingly, the Triac 420 is conducting current (indicated by the shaded areas) during an end portion 512 of half-cycle 502 from time T1 to time T2, and again during an end portion 514 of half-cycle 504 from time T3 to time T4. Accordingly, the lamp is on (i.e. illuminated and emitting heat energy) during the end portions 512, 514.

[0046] Considering now a method of operating a Triac-controlled lamp at a specified power level, and with reference to FIG. 6 and continued reference to FIG. 5, a method 600 computes for the lamp, using the power level and instantaneous voltage and current of the lamp while illuminated during a present half-cycle of AC power applied to the lamp, a turn-on time of the corresponding Triac for a next half-cycle.

[0047] The method 600 begins at 610 by measuring the instantaneous voltage (V_{inst}) and current (I_{inst}) of the lamp while the Triac is conducting during a present half-cycle 502 of AC power. The instantaneous voltage and current are measured during an end portion, such as end portion 512. In some examples, the instantaneous voltage and current are measured during the end portion within $\langle n \rangle$ milliseconds after the Triac has been turned on. The instantaneous voltage and current may be measured by a voltage detector 430 and a current detector 440 (FIG. 4) respectively.

[0048] The instantaneous voltage and current measured for the present half-cycle 502 are used, along with a requested power level for the lamp, to compute the turn-on time for the Triac for the next half-cycle 504. More specifically, at 620, an instantaneous resistance (R_{inst}) of the lamp is calculated from the measured voltage and current, as $R_{inst} = V_{inst} / I_{inst}$. At 630, a turn-on time of the Triac for the next half-cycle 504 is computed based on the specified power level and the instantaneous resistance. One example

of computing the turn-on time is described subsequently in greater detail with reference to FIG. 7.

[0049] As has been described, the Triac automatically turns off at time T2 (the end of half-cycle 502). At 640, during the next half-cycle 504, the Triac is turned on at the computed turn-on time (time T3) by the application of an appropriate turn-on signal issued by the lamp controller to the gate of the Triac.

[0050] Measuring the instantaneous lamp voltage and current during each half-cycle of the AC waveform allows the actual resistance of the lamp during that half-cycle to be accurately calculated. This accounts for the changes in lamp resistance that occur as the filament temperature changes, changes which may be more pronounced when the lamp is operating at lower requested power levels. As a result, the resistance which is used to calculate the turn-on time for the next half-cycle is obtained close in time to the next half-cycle. This allows an accurate voltage to be applied to the lamp during the next half-cycle in order to accurately achieve the requested power level.

[0051] Considering now another method of operating a Triac-controlled lamp at a specified power level, and with reference to FIG. 7 and continued reference to FIG. 5, a method 700 begins at 710 by turning on the Triac during an initial half-cycle of an AC waveform at a turn-on time determined based on a specified power level and a resistance of the lamp at a cold temperature. The initial half-cycle may be, for example, the first cycle during which an AC waveform from an AC source (such as AC source 410, FIG. 4) is applied to a heating lamp array 150 (FIG. 1)

[0052] At 720, the instantaneous voltage (V_{inst}) across, and current (I_{inst}) through, the lamp is measured during an end portion of a present half-cycle of an AC waveform (such as, for example, from an AC power source) which is applied to the lamp. The AC waveform is applied to the lamp when the Triac which is connected in series with the AC power source and the lamp to control the lamp's illumination is conducting. In some examples, multiple measurements of the instantaneous voltage and/or current may be taken

during the end portion of the present half-cycle, and the measurements averaged to form V_{inst} and/or I_{inst} .

[0053] At 730, an instantaneous resistance (R_{inst}) of the lamp is calculated from the measured voltage and current as $R_{inst} = V_{inst} / I_{inst}$.

[0054] At 740, a turn-on time of the Triac (T_{turnon}) for a next half-cycle of the AC waveform is computed based on the specified power level ($P_{requested}$) and the instantaneous resistance (R_{inst}). In some examples, the specified power level is a percentage of the rated power of the lamp. In some examples, at 742, an adjusted power ($P_{adjusted}$) is computed according to the formula $P_{adjusted} = P_{requested} * R_{inst} / R_{hot}$, where R_{hot} is the specified or predetermined rated resistance of the lamp when it is operating at full rated power. This has the effect of normalizing the requested power for the present resistance of the lamp. The Triac turn-on time for the next half-cycle is then calculated from the adjusted power level and the instantaneous resistance. At 744, a commutation time ($T_{commutation}$) is determined as a function of $P_{adjusted}$. The commutation time is the duration of time at the end portion of the half-cycle during which the Triac is turned on and conducting. At 746, the turn-on time (T_{turnon}) is then computed by subtracting $T_{commutation}$ from the period of a half-cycle.

[0055] In one example, the commutation time is determined at 744 according to a sinusoidal AC waveform, which may be an ideal sine wave. In an ideal sinewave, the power delivered to an ideal resistor is calculated as $P(t) = V(t) \cdot I(t)$, and during a small fraction of time we can approximate to $P(t) = [V \cdot \sin(\omega \cdot t)]^2 / R$. The energy applied during a certain period of time equals the integral of this $P(t)$ as per the formula $E(t_{on}) = \text{INTEGRAL}[t_{on}, t_{off}]\{P(t) \cdot dt\}$, where t_{on} is the time the TRIAC is turned on, and t_{off} is the time when the AC voltage crosses zero and the TRIAC turns off. The average power during this portion of cycle (instantaneous power) $P_{inst} = E(t_{on}) / (t_{off} - t_{on})$. At each cycle t_{on} is computed in order to obtain the desired P_{inst} . In one example, this calculation is performed by plotting the real voltage curve $V(t)$, computing $V(t)^2$, calculating the integral, extrapolating with a 3rd degree polynomial, and resolving the equation. In

some examples, these calculations may be performed accurately in real time by a lamp controller. In other examples, an off-line approximation can be made assuming a sinusoidal voltage and using a table of values (i.e. a lookup).

[0056] The following example illustrates the computation of T_{turnon} . Assume that the AC waveform is 50 hertz, $P_{\text{requested}} = 30\%$, and $R_{\text{hot}} = 30$ ohms. In addition, assume that the lamp has been operating at a less than full power level such that R_{inst} (as determined from the measured V_{inst} and I_{inst}) is 20 ohms. In this case, $P_{\text{adjusted}} = 30\% * 20 \text{ ohms} / 30 \text{ ohms} = 20\%$. A half-cycle period is 10 milliseconds. Applying the function to a P_{adjusted} value of 20% yields a $T_{\text{commutation}}$ of $25\% * 10 \text{ milliseconds} = 2.5$ milliseconds. $T_{\text{turnon}} = 10 \text{ msec} - 2.5 \text{ msec} = 7.5 \text{ msec}$.

[0057] At 750, a zero crossing indicative of the end of the present half-cycle and the start of the next half-cycle is detected.

[0058] At 760, the Triac is turned on at the turn-on time (T_{turnon} ; 7.5 msec in the preceding example) during the next half-cycle. After this, the method 700 continues at 720 to repeat the process using the next half-cycle of 760 as the present half-cycle of 720.

[0059] In block 710, the turn-on time (T_{turnon}) for the initial half-cycle is computed in an analogous manner to block 740, substituting a specified value for the resistance of the lamp at a cold filament temperature (R_{cold}) for R_{inst} in the calculation of adjusted power which is performed at 742. In one example, $R_{\text{cold}} = R_{\text{hot}} / 15$.

[0060] Considering now one example lamp controller, and with reference to FIG. 8, a lamp controller 800 includes a computer-readable storage medium 820, which may be a memory, having processor-readable and/or processor-executable instructions stored thereon, such as the firmware or software instructions, including instructions to perform at least some portions of the method 600 (FIG. 6) and/or method 700 (FIG. 7). The medium 820 is communicatively coupled to a processor 810 to access and execute the instructions. The storage medium may include different forms of memory including semiconductor memory devices such as DRAM, or SRAM, Erasable

and Programmable Read-Only Memories (EPROMs), Electrically Erasable and Programmable Read-Only Memories (EEPROMs) and flash memories; magnetic disks such as fixed, floppy and removable disks; other magnetic media including tape; optical media such as Compact Disks (CDs) or Digital Versatile Disks (DVDs); and/or other types of computer-readable storage devices. In some examples, the controller 170 (FIG. 1) or 340 (FIGS. 3-4) may be, or include, the controller 800.

[0061] The storage medium 820 includes a module and/or set of instructions 830 to measure V_{inst} and I_{inst} . The storage medium 820 also includes a module and/or set of instructions 840 to compute the Triac turn-on time. The storage medium 820 further includes a module and/or set of instructions 850 to control turn-on of the Triac, which in some examples also includes a module and/or set of instructions 855 to detect zero crossing of an AC waveform.

[0062] Note that the instructions of the firmware and/or software discussed above can be provided on one computer-readable or computer-usable storage medium, or alternatively, can be provided on multiple computer-readable or computer-usable storage media distributed in a large system having possibly plural nodes. Such computer-readable or computer-usable storage medium or media is (are) considered to be part of an article (or article of manufacture). An article or article of manufacture can refer to any manufactured single component or multiple components.

[0063] In some examples, at least one block discussed herein is automated. In other words, apparatus, systems, and methods occur automatically. As defined herein and in the appended claims, the terms "automated" or "automatically" (and like variations thereof) shall be broadly understood to mean controlled operation of an apparatus, system, and/or process using computers and/or mechanical/electrical devices without the necessity of human intervention, observation, effort and/or decision.

[0064] Terms of orientation and relative position (such as "top," "bottom," "side," and the like) are not intended to indicate a particular orientation of any

element or assembly, and are used for convenience of illustration and description.

[0065] From the foregoing it will be appreciated that the systems and methods provided by the present disclosure represent a significant advance in the art. Although several specific examples have been described and illustrated, the disclosure is not limited to the specific methods, forms, or arrangements of parts so described and illustrated. For example, examples of the disclosure are not limited to power control of lamps used in additive manufacturing systems, nor to tungsten and tungsten-halogen lamps. This description should be understood to include all combinations of elements described herein, and claims may be presented in this or a later application to any combination of these elements. The foregoing examples are illustrative, and different features or elements may be included in various combinations that may be claimed in this or a later application. Unless otherwise specified, operations of a method claim need not be performed in the order specified. Similarly, blocks in diagrams or numbers (such as (1), (2), etc.) should not be construed as operations that proceed in a particular order. Additional blocks/operations may be added, some blocks/operations removed, or the order of the blocks/operations altered and still be within the scope of the disclosed examples. Further, methods or operations discussed within different figures can be added to or exchanged with methods or operations in other figures. Further yet, specific numerical data values (such as specific quantities, numbers, categories, etc.) or other specific information should be interpreted as illustrative for discussing the examples. Such specific information is not provided to limit examples. The disclosure is not limited to the above-described implementations, but instead is defined by the appended claims in light of their full scope of equivalents. Where the claims recite “a” or “a first” element of the equivalent thereof, such claims should be understood to include incorporation of at least one such element, neither requiring nor excluding two or more such elements. Where the claims recite “having”, the term should be understood to mean “comprising”.

What is claimed is:

1. A power control system for a lamp, comprising:
 - a Triac having main terminals connectable in series with an AC power source and the lamp;
 - a voltage detector connectable across the lamp;
 - a current detector connectable in series with the lamp; and
 - a controller connected to the voltage detector, the current detector, and a gate of the Triac to
 - measure instantaneous voltage and current of the lamp when the Triac is conducting during a present half-cycle of AC power,
 - compute a turn-on time of the Triac for a next half-cycle using a specified lamp power level and the instantaneous voltage and current, and
 - turn the Triac on at the turn-on time during the next half-cycle.
2. The system of claim 1, wherein the lamp is a tungsten-halogen lamp having a temperature-dependent resistance.
3. The system of claim 1, wherein the specified lamp power level is a percentage from 0% to 100% of a rated full power of the lamp.
4. The system of claim 3, wherein the lamp is continuously operable at a specified power level of 30% or less while maintaining peak current through the lamp below a maximum rated current of the lamp.
5. The system of claim 1, wherein to compute the turn-on time the controller is further to:
 - calculate an instantaneous resistance of the lamp from the measured voltage and current;
 - compute an adjusted power level by multiplying the specified power level by the instantaneous resistance divided by a rated resistance of the lamp when operating at full rated power; and

compute the Triac turn-on time for the next half-cycle using the adjusted power level and the instantaneous resistance.

6. The system of claim 1, comprising:
a zero-crossing detector connected to the controller and connectable across the lamp to signal a beginning of each half-cycle.

7. An additive manufacturing system, comprising:
at least one sensor to detect temperatures of plural regions of a build bed;
an array of heating lamps disposed above the build bed, each lamp associated with one of the regions and having a corresponding Triac to independently control the lamp; and
a controller to
determine, using the temperatures, a requested power level for each lamp,
compute for each lamp, using the corresponding power level and instantaneous voltage and current of the lamp while illuminated during a present half-cycle of AC power applied to the lamp, a turn-on time of the corresponding Triac for a next half-cycle, and
turn each Triac on at the corresponding turn-on time during the next half-cycle.

8. The system of claim 7, wherein to compute the turn-on time for each lamp the controller is further to:

calculate an instantaneous resistance of the lamp from the measured voltage and current;

compute an adjusted power level by multiplying the requested power level by the instantaneous resistance divided by a rated resistance of the lamp when operating at full rated power; and

compute the Triac turn-on time for the next half-cycle using the adjusted power level and the instantaneous resistance.

9. The system of claim 7, wherein different ones of the plural regions of the build bed have different detected temperatures, and wherein the requested power level of each lamp is chosen to reduce temperature differences among the plural regions.

10. The system of claim 7, wherein a top layer of build material in a particular region of the build bed corresponds to a feature of a 3D object being fabricated in the build bed, and wherein the requested power level of a lamp associated with that region is chosen to provide energy for fusing a portion of the top layer in the particular region which corresponds to the feature.

11. A method of controlling a Triac-controlled tungsten halogen lamp at a specified power level, comprising:

- measuring instantaneous voltage and current of the lamp during an end portion of a present half-cycle of an AC waveform applied to the lamp;
- calculating an instantaneous resistance of the lamp from the measured voltage and current;
- computing a turn-on time of the Triac for a next half-cycle based on the specified power level and the instantaneous resistance; and
- turning the Triac on at the turn-on time during the next half-cycle.

12. The method of claim 11, wherein the specified power level is a percentage of the rated power of the lamp, and wherein the computing the turn-on time comprises:

- computing an adjusted power level by multiplying the specified power level by the instantaneous resistance in the present half-cycle divided by a rated resistance of the lamp when operating at full rated power; and
- calculating the Triac turn-on time for the next half-cycle from the adjusted power level and the instantaneous resistance.

13. The method of claim 11, wherein calculating the Triac turn-on time for the next half-cycle comprises:

determining a commutation time for the Triac as a function of the adjusted power level according to a sinusoidal AC waveform; and

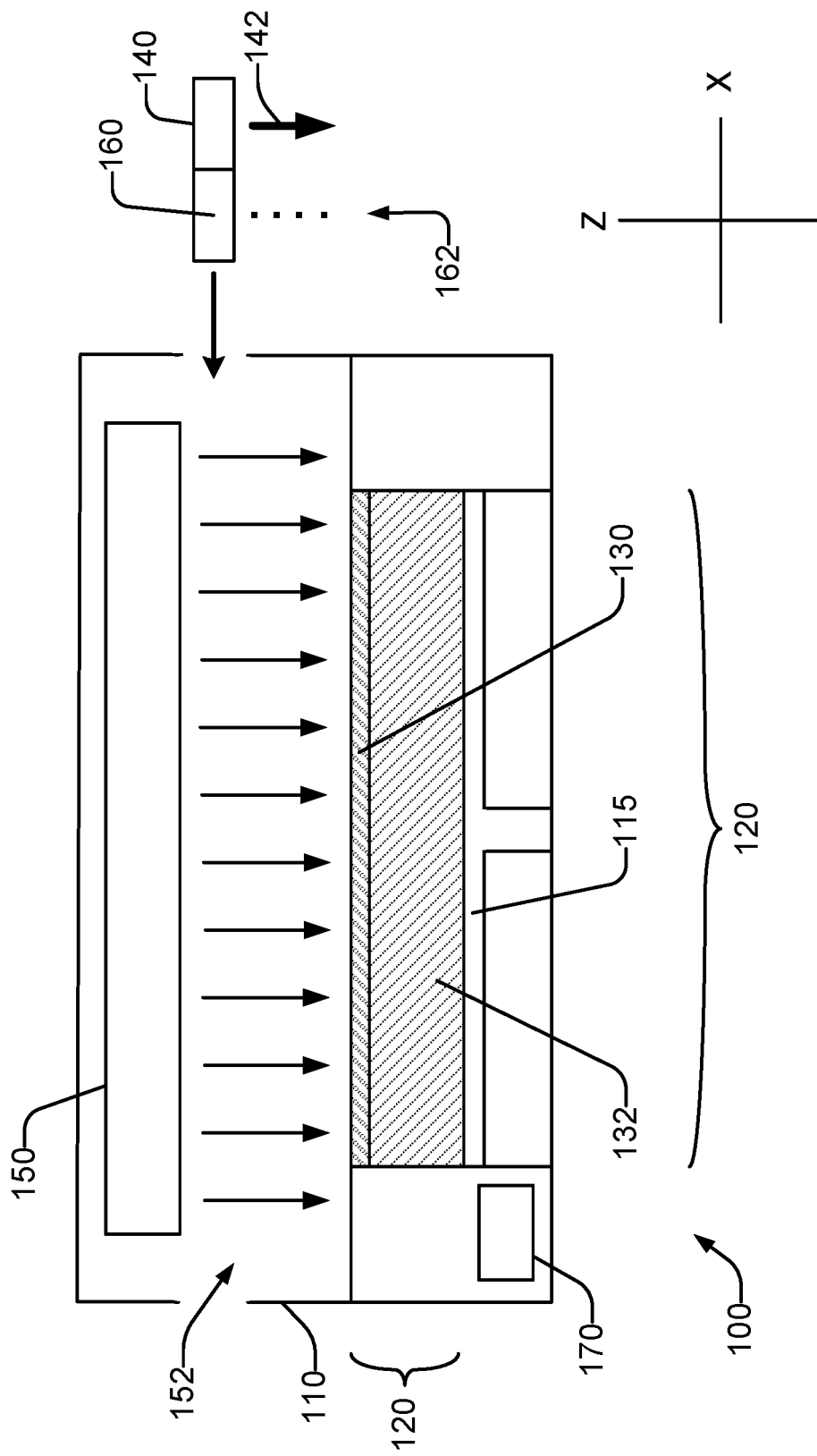
subtracting the commutation time from a period of a half-cycle of the AC waveform to form the turn-on time.

14. The method of claim 11, comprising:

determining a turn-on time of the Triac for an initial half-cycle of the AC waveform based on the specified power level and a resistance of the lamp at a cold temperature.

15. The method of claim 11, wherein the measuring is performed plural times during the end portion of the present half-cycle, and wherein the measured voltage and current each comprise an average of the plural measurements.

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**Fig. 1**

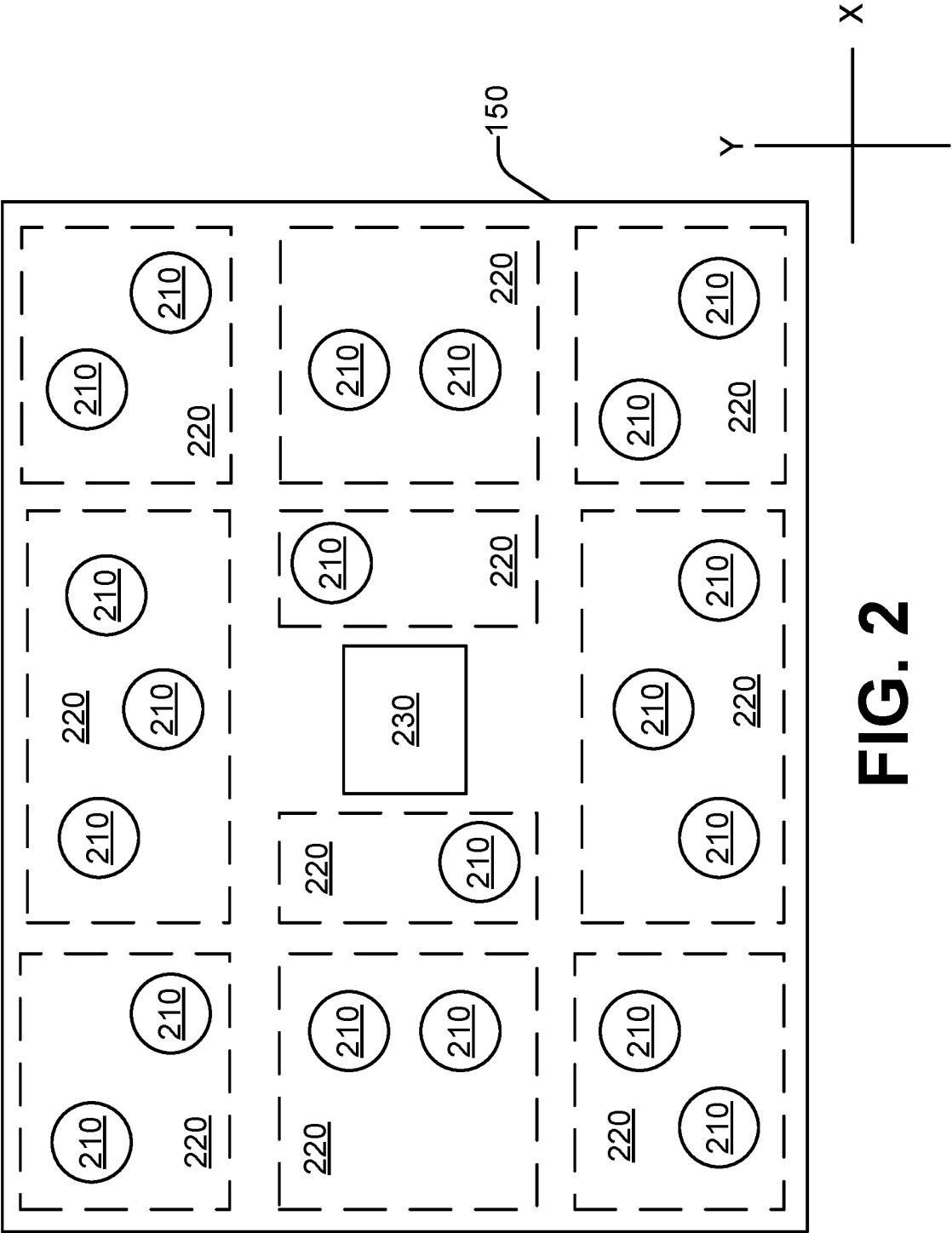


FIG. 2

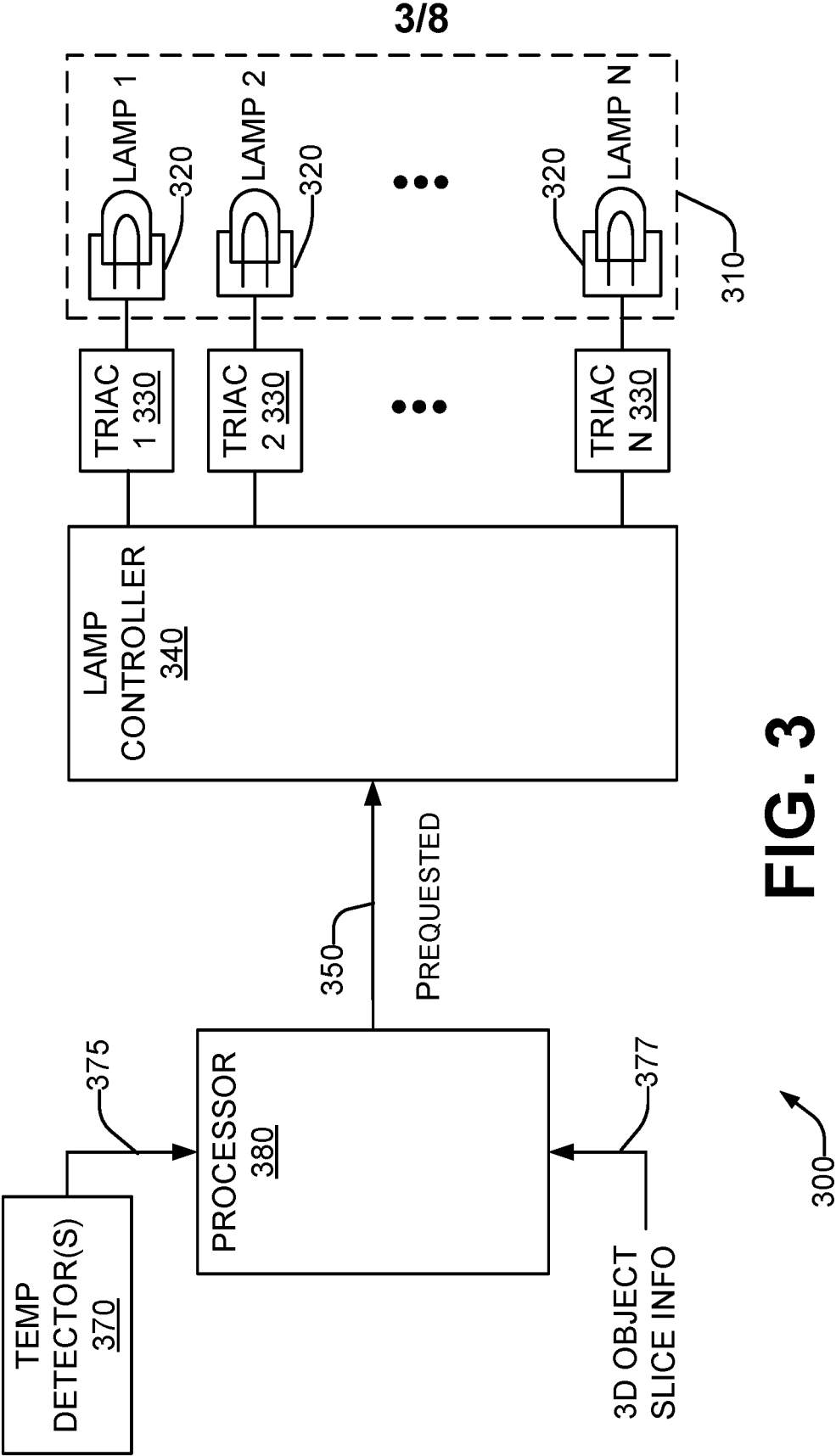


FIG. 3

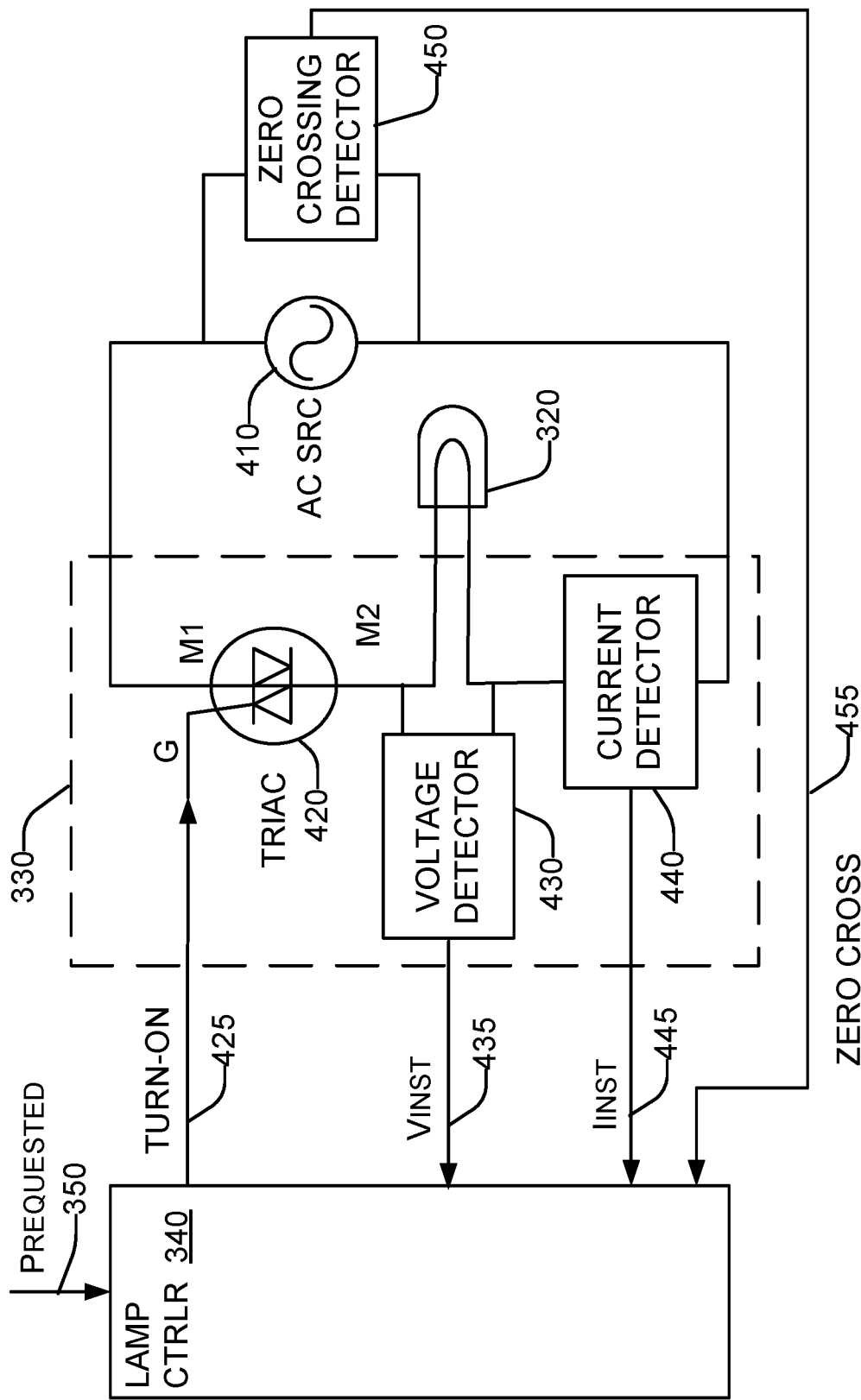


FIG. 4

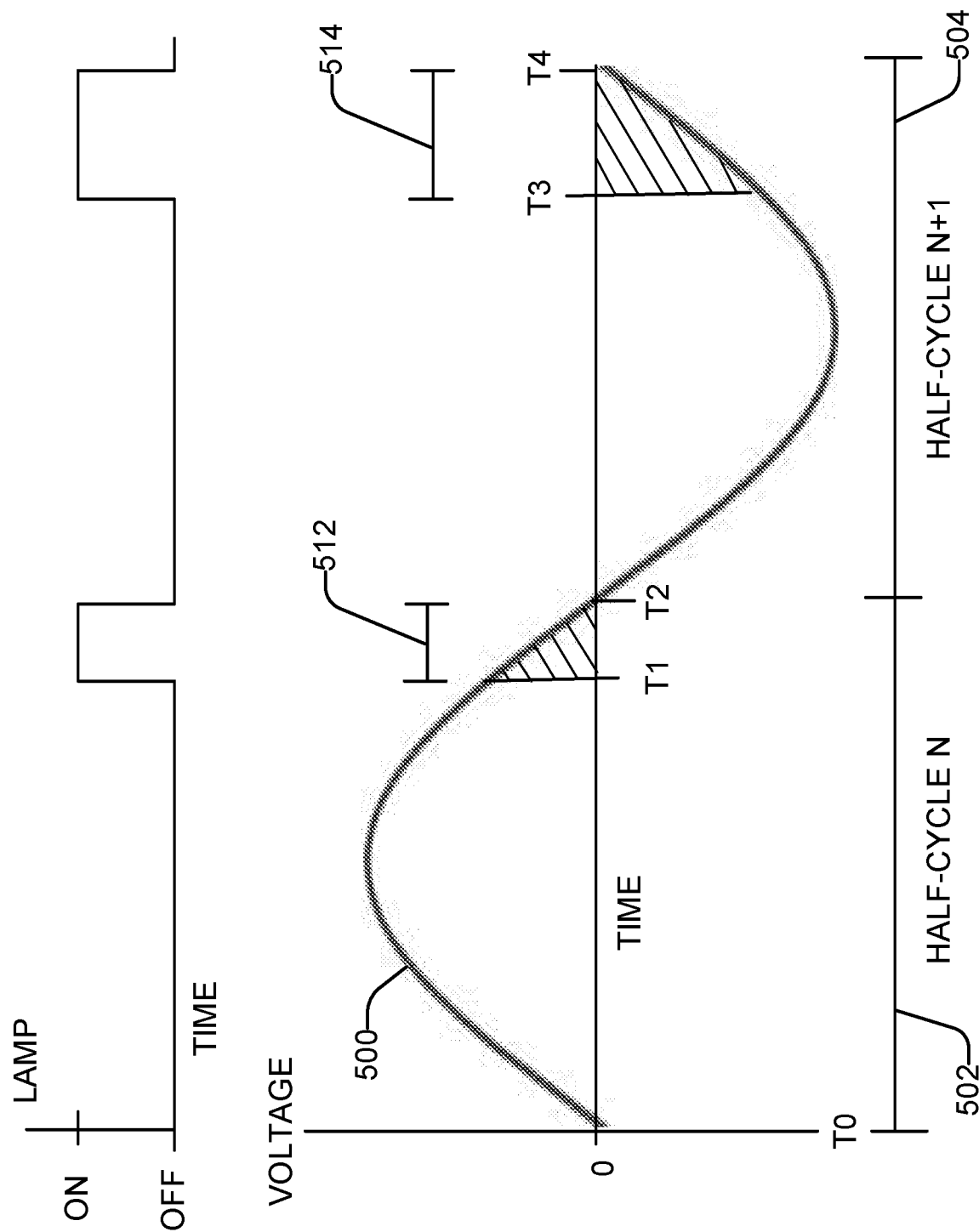
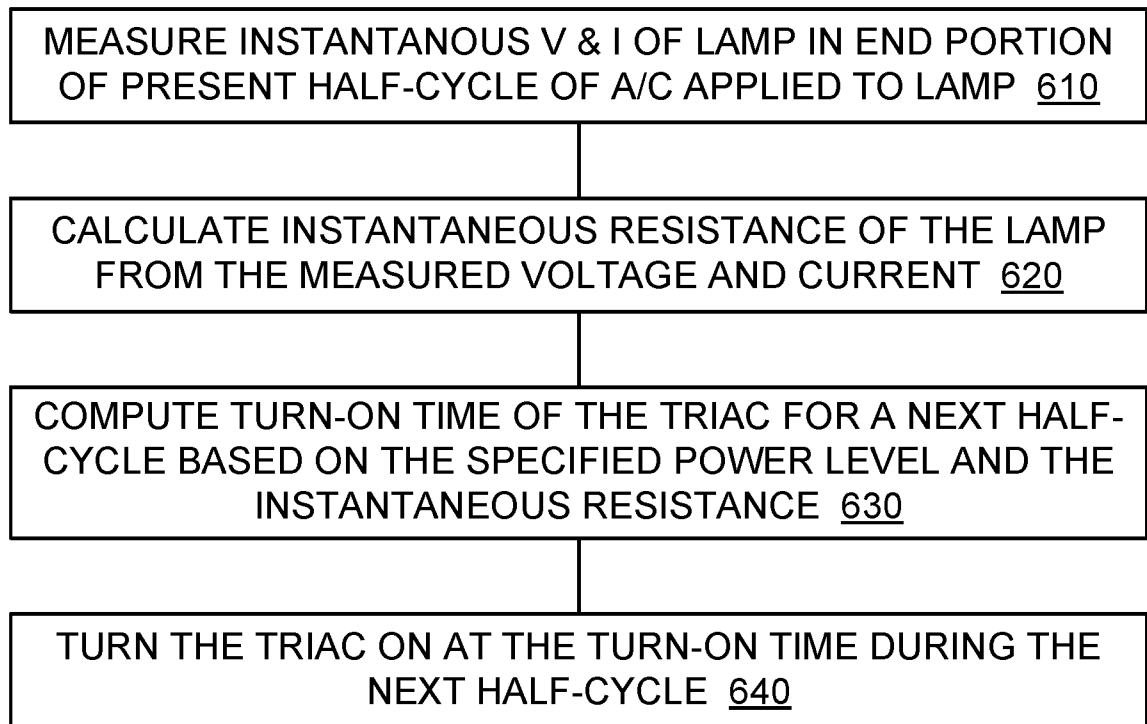
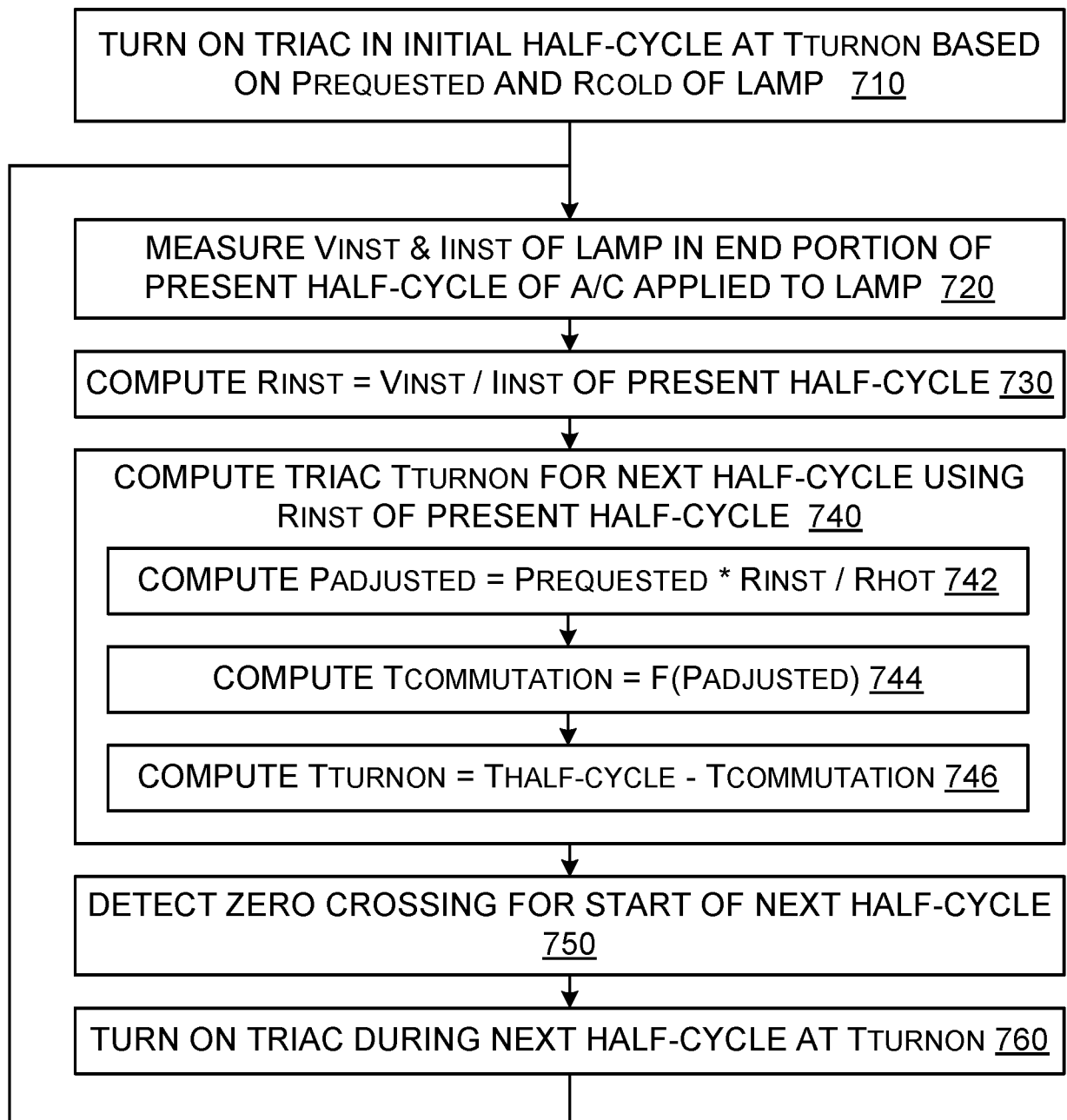


FIG. 5

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600 **FIG. 6**

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700

FIG. 7

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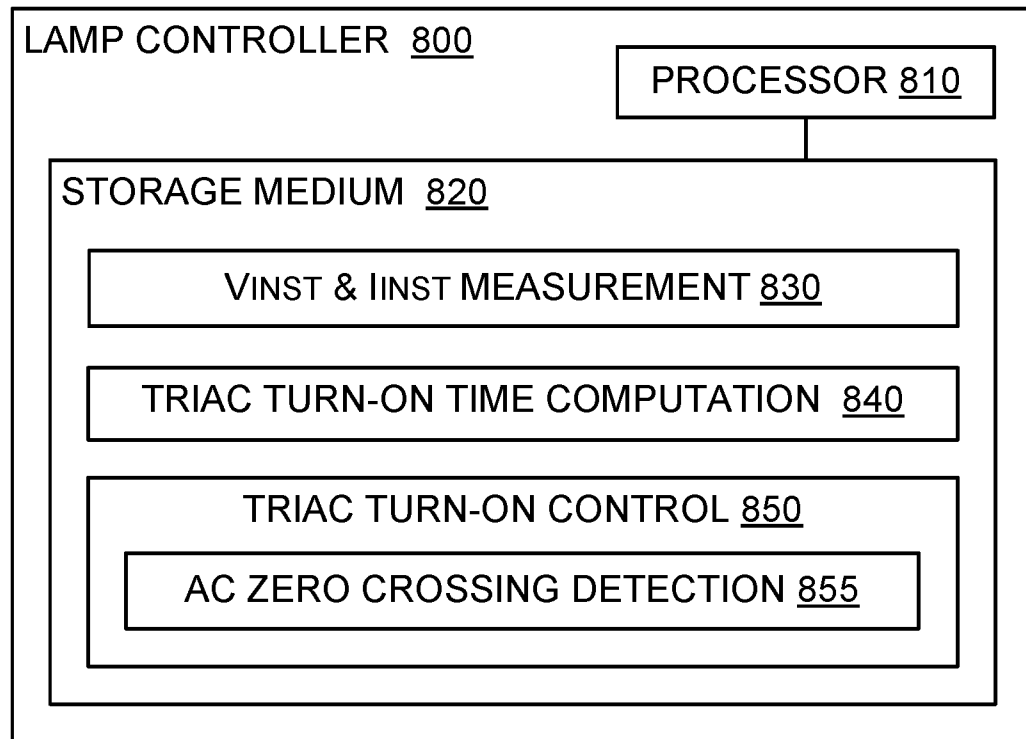


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2017/029432

A. CLASSIFICATION OF SUBJECT MATTER		
H05B 39/04 (2006.01)		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols)		
H05 B 37/00-37/04, 39/00-39/10		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)		
PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, DWPI, EAPATIS, PATENTSCOPE		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	RU2262216 C1 (БУГРИН АЛЕКСЕЙ ВЛАДИМИРОВИЧ и др.) 10.10.2005	1-15
A	US4675578 A (BRIGHTER LIGHT LITURGICAL FURNISHINGS, INC.) 23.06.1987	1-15
A	US 8680771 B2 (CIRRUS LOGIC, INC.) 25.03.2014	1-15
☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search		Date of mailing of the international search report
22 January 2018 (22.01.2018)		31 January 2018 (31.01.2018)
Name and mailing address of the ISA/RU: Federal Institute of Industrial Property, Berezhkovskaya nab., 30-1, Moscow, G-59, GSP-3, Russia, 125993 Facsimile No: (8-495) 531-63-18, (8-499) 243-33-37		Authorized officer O. Schedrina Telephone No. 8 499 240 25 91