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(54) **Method of controlling the current of a flash lamp**

(57) The present invention relates to methods of controlling the current of a flash lamp, particularly, it relates to methods of controlling the current of a flash lamp in which during periods of time between main discharge pulses the flash lamp is simmered thus extending the flash lamp's service life and stabilizing its gas discharge channel, and can be used for driving pump lamps of pulsed lasers. The method comprises delivering of main current pulses to the flash lamp that cause an intense gas discharge. During the major part of time interval between adjacent main current pulses a strength of the simmer current is maintained at a first strength level, which

is as low as possible while still ensures an existence of the discharge channel, whereas prior to delivering each of said main current pulses, the simmer current is increased to a second strength level and is selected to be equal to a lowest possible current strength level that is sufficient to ensure that the tube of said flash lamp is entirely and uniformly filled with plasma. In another embodiment, prior to delivering each of the main current pulses, the simmer current is being increased until resistance of the flash lamp becomes equal to the value with which the main discharge phase begins with a monotonic voltage growth.

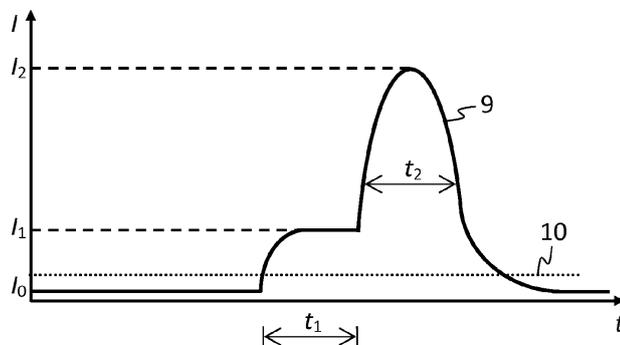


Fig.2

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Description

[0001] The present invention relates to methods of controlling the current of a flash lamp, particularly, it relates to methods of controlling the current of a flash lamp in which during periods of time between main discharge pulses the flash lamp is simmered thus extending the flash lamp's service life and stabilizing its gas discharge channel, and can be used for driving pump lamps of pulsed lasers.

[0002] During an electrical discharge in a gas an optical radiation is generated which has many uses in industry, science and medicine. Gas-discharge lamps are widely used for pumping laser sources. The most common application of flash lamps, which are pulsed gas-discharge lamps, is pumping of high power pulsed lasers.

[0003] Industrial laser systems must meet several basic requirements: reliability and simple maintenance. In industrial material processing such as cutting, drilling or welding laser system needs to be exploited non-stop, therefore, it is very desirable that characteristics of the system should not deteriorate quickly and the time between consecutive maintenance operations should be as long as possible. One of the most rapidly deteriorating elements in these systems are flash lamps used for pumping. Their service life (which is much like the same as a lifetime but hereinafter refers to the period of time not until a fracture of the lamp but until its significant degradation) depend both on lamp's technical specifications and on its operating mode. In addition, the reliability of the system is determined by laser output energy repeatability and its propagation direction stability. Again, it is largely related to the pump lamp's radiation properties.

[0004] In WO9213358, US5168194, JP2007287563 specific designs of gas-discharge lamps are described that help to extend lamp's service life and/or to stabilize a location of the gas discharge channel. A disadvantage of these lamps is that manufacturing of special geometry electrodes may be complicated and expensive compared to conventional geometry ones. Most powerful industrial systems use flash lamps of a very simple design whereas the discharge stability and the long service life are ensured by controlling the current supplied to the flash lamp.

[0005] It is known that the service life of a flash lamp can be extended by keeping the lamp on during time periods between main discharge pulses. When the lamp is being ignited, the current flow between its electrodes is sustained. During time periods between delivering main discharge current pulses a so called keep-alive or simmer current is being supplied. This type of flash lamp's driving is presented in W.Koehnner, Solid-State Laser Engineering, 6th ed., Springer, Berlin (2006), US3551738, US3967212, US5315607, US4398129, US4910438. Here, a strength of the simmer current is maintained constant or varies within a narrow range of values.

[0006] The method can be described as follows. After a flash lamp's ignition by a high voltage triggering pulse,

a conducting path (which also may be referred to as a discharge channel or an arc) between lamp's electrodes is established. Therefore, conditions for the current flow are created. Before the first and between any two adjacent main discharge current pulses which are characterized by a high value of a current strength to cause an intense plasma glow, a low-strength simmer current is supplied. As a result, a partial ionization of the lamp is maintained. The discharge at this phase is still a streamer, not filling the lamp's tube, or, at extremely low current level, it is an irregular arc similar to atmospheric lightning. The higher value of the simmer current strength, the larger diameter of the discharge channel. Moreover, the discharge channel with a larger diameter is characterized by a higher stability.

[0007] Flash lamp simmering is beneficial because of the elimination of the need to repetitively ignite the lamp. Also, with the simmer mode of operation an expansion of plasma at the very beginning of the main discharge phase is less violent. Moreover, the main discharge in the flash lamp in which conduction path has been established is more reliable and the resulting optical radiation is characterised by higher stability.

[0008] A drawback of the above-described method is a too large consumption of the lamp. Flash lamp's service life is directly dependent on the charge that flows through the lamp. There are two parameters that should be taken into account when trying to estimate the lamp's consumption and a meaningfulness of the simmer method thereof: a simmer phase duration and a simmer current strength.

[0009] For low repetition rate systems the time interval between two adjacent main discharge pulses is sufficient to allow resistance, current and voltage fluctuations initiated by lamp's triggering to relax. In this case continuous simmering of the flash lamp is meaningless because the charge that flows through the flash lamp during the simmer phase may exceed the charge that flows through the flash lamp during the main discharge phase. Therefore, the drawback of a large lamp's consumption overshadows the benefits of the simmer method.

[0010] When the time interval between two adjacent main discharge pulses is comparable with the time required for fluctuations due to triggering to relax and for the discharge channel to be formed (moderate pulse repetition rate), the trade-off between benefits and drawbacks of the simmer method should be made.

[0011] While in high repetition rate systems (applications including most industrial solid state laser systems) flash lamp's driving with the simmer mode of operation, in most cases, has more advantages than disadvantages.

[0012] The strength of the simmer current determines which part of the charge flowing through the lamp is not used for production of useful optical radiation. The higher the strength of the simmer current, the larger lamp's consumption. On the other hand, with an extremely low simmer current the arc inside lamp's tube is very unstable. It may get extinguished or strongly fluctuates in space

and time what affects an evolution of the main discharge. Unstable arc at the simmer phase results in spatial and energy instabilities of the main discharge pulse what in turn reflects in laser output stability and efficiency. Additionally, changes of ionized volume inside lamp's tube are accompanied by fluctuations of lamp's resistance, voltage and current bearing electromagnetic noise which disturbs other electric devices.

[0013] In the above-mentioned method with a constant value of the simmer current strength it is impossible to achieve high stability of discharge channel without strongly consuming a flash lamp. On the other hand, a long flash lamp's service life may be achieved at the expense of output radiation stability. An optimum value of the simmer current strength for a given pulse repetition rate should be selected by considering all said factors. In the systems of the known solutions with a constant simmer current, typical values of the simmer current strength vary within a range between 50mA and 1A [see descriptions of patents US4910438, US5168194, US5373215 and Alex D. McLeod, "Design Considerations for Triggering of Flash lamps", Nov. 1996. Copyright© 1998-2003 PerkinElmer, Inc.]. As for example, 500mA simmer current at 50Hz pulse repetition gives a charge flowing through the flash lamp during the simmer phase comparable with a charge of the main discharge phase. Here, system efficiency and output stability are of the main priority and the lamp's service life is sacrificed.

[0014] In U.S. patent US6330258 a method of laser pump lamps' driving is presented which comprises a flash lamp's simmering between the main discharge pulses, whereas the simmer current strength is adapted to the pulse repetition rate: 0.3A for low rate zone (below 2Hz), 2A for medium rate zone (from 2Hz to 200Hz) and 5A for high rate zone (above 200Hz). Besides, at standby periods between burst of pulses the lamp is maintained at the lowest available simmer current level (0.3A). Within a burst of pulses the simmer current is constant.

[0015] In the described solution the effect of extended service life of the pump lamps is achieved just because during standby periods between bursts of pulses the lowest available current strength value is selected. Therefore, lamps' consumption is the lowest compared to consumptions that would be with other current strength values. For repetitively pulsing flash lamps the solution of US6330258 patent coincides with the one-level-simmer-current solutions discussed above.

[0016] An international application of invention WO2008003997 discloses yet another method of a laser pump lamp current control involving a simmer mode of operation with improvements made to enhance overall operational stability. Its major aim is to stabilize thermal conditions of a laser gain medium. Therefore, a pump lamp's simmer current strength value is selected so that thermal load upon the laser gain medium at lamp's simmering is similar to the thermal load occurring at laser generation. It is particularly important at laser start up or at start up of every burst of pulses. During standby peri-

ods the pump lamp is fed by a nominal value simmer current, while prior to the first main discharge pulse an increased simmer current level is supplied to the lamp. This way, the laser gain medium is thermally preloaded prior to laser generation. Although the simmer current strength may vary between operating cycles within a burst, it is maintained constant during one cycle and its level is higher than the nominal simmer level to have thermal load upon laser gain medium similar to that of laser generation.

[0017] This solution aiming to equalize thermal conditions does not preserve the lamp. In order to get thermal load at simmer phase similar to that occurring at laser generation, the lamp's simmer current strength must be relatively high close to laser generation threshold. This strongly consumes the pump lamp and required a powerful simmer supply.

[0018] The methods of controlling the current of the flash lamp using the one-level simmer current in principal cannot simultaneously provide a long lamp's service life and high radiation stability. A trade-off between these desirable properties must be made. In most cases, the strength of simmer current is selected to ensure high stability resulting in a shorter flash lamp's service life.

[0019] In US4276497, WO2008003997, US2008157695 methods of controlling the current of a flash lamp are presented in which the simmer current between two adjacent main discharge pulses is variable. A time dependence of the simmer current strength during one lamp's operating cycle may be described by a certain algorithm or determined dynamically with the use of real-time feedback loops.

[0020] However, at high pulse repetition rates, real-time parameter monitoring and control is difficult to implement. Fast control of system parameters requires a very powerful source. All of the above mentioned solutions of flash lamps' driving focus on overall stability and system efficiency improvements as well as on pulse timing jitter minimization. Therefore, the flash lamp's service life suffers.

[0021] U.S. patent application US2008157695 (Lantis et al.) discloses a power supply system which is impedance-matched with a flash lamp throughout the time span despite the varying load of the lamp during ignition, simmer, and main discharge phases. This helps to prevent lamp envelope fracture, and a more reliable operation is achieved. The simmer current strength is dynamically adjusted in a real time. Thus, the current waveform is of some irregular shape which is determined by instantaneous values of the lamp and the power supply impedance mismatch and varies from lamp to lamp, also depends on lamp's degradation in time. The solution of US2008157695 is complex, while the precise impedance-matching requirement is essential only for high power UV lamps described therein.

[0022] *Burbeck et al.* in U.S. patent US4276497 describe another method of the flash lamp's driving in which a duration and a shape of the main current pulses are

easily controlled whereas between main pulses the lamp is continuously simmered. In one of the embodiments the strength of the simmer current can be raised immediately prior to the main pulse. This results in a faster main pulse build-up and also preserves the lamp from current and voltage jumps during transition from the simmer phase to the main discharge phase. However, the level of the simmer current which is needed to maintain current flow in the *Burbeck's* lamp is relatively high because the simmer current is generated from a low impedance source. Therefore, a large amount of charge passes and the lamp is strongly consumed. The above-described method does not provide an optimal waveform of the current supplied to a flash lamp for ensuring high stability of the flash lamp and attaining the longest possible lamp's service life.

[0023] The aim of the present invention is to extend a service life of a flash lamp while still ensuring high stability of lamp's output radiation.

[0024] According to the invention, this problem is solved by the method of controlling the current of a flash lamp, when main discharge pulses of a current are delivered to the flash lamp causing an intense gas discharge, where the main discharge pulses are triggered by synchronization pulses, while during the time intervals between said main discharge pulses the flash lamp is supplied with a continuous simmer current, a strength of which is increased prior to delivering each of said main discharge pulses, wherein during the major part of time interval between adjacent main discharge pulses a strength of the simmer current is maintained at a first level, which is as low as possible while still ensures an existence of the discharge channel; whereas prior to supplying each of said main discharge pulses, a first synchronization pulse switches the simmer current to a second strength level, which is higher than said first strength level. The second strength level depends on the flash lamp parameters and is equal to a lowest possible current strength level that is sufficient to ensure that the tube of said flash lamp is entirely and uniformly filled with plasma, further, a second synchronization pulse, which is delayed with respect to said first synchronization pulse by a predetermined time interval, triggers the main discharge pulse. Said predetermined time interval is the shortest possible time interval for the flash lamp to be entirely and uniformly filled with plasma.

[0025] By controlling the current of a flash lamp according to the method of this invention a balance between an extended lamp's service life (which requires the lowest possible simmer current strength) and stability of the discharge channel (for which increased current strength levels are preferable) may be achieved. Since during the major part of the simmer phase the lowest possible the current first strength level is maintained, the arc does not get extinguished while flash lamp's consumption is reduced to a minimum. On the other hand, the increased simmer current second strength level preconditions the flash lamp for the main discharge: a tube of the lamp gets

entirely and uniformly filled with plasma. Moreover, said increased simmer current second strength level is as low as possible that is enough to ensure lamp's filling and the time interval when said increased simmer current level is on, is equal to the shortest time interval for fluctuations of plasma to relax. Stabilized plasma at the beginning of the main discharge ensures energy and spatial stability of flash lamp's radiation, as well as low jitter of output pulses. Therefore, by using the method of this invention, flash lamp's service life is extended without spoiling radiation stability. This guarantees reliability, low cost and simple maintenance of the system. Secondly, the method of this invention allows for reducing the level of electromagnetic noise.

[0026] Another embodiment of the present invention is method of controlling the current of a flash lamp when main discharge pulses of a current are delivered to the flash lamp causing an intense gas discharge, where the main discharge pulses are triggered by synchronization pulses, while during the time intervals between said main discharge pulses the flash lamp is supplied with a continuous simmer current, a strength of which is increased prior to delivering each of said main discharge pulses, wherein during the major part of time interval between adjacent main discharge pulses a strength of the simmer current is maintained at a first strength level, which is as low as possible while still ensures an existence of the discharge channel, whereas prior to delivering each of said main discharge pulses;

a first synchronization pulse triggers increasing of the simmer current strength until flash lamp's resistance achieves a predetermined resistance value, which depends on the flash lamp parameters and is equal to a resistance with which the main discharge phase in said flash lamp begins with a voltage growth; further, a second synchronization pulse, which is delayed with respect to said first synchronization pulse by a predetermined time interval (t_1), triggers the main discharge pulse, whereas said predetermined time interval (t_1) is the shortest possible time interval to achieve said predetermined resistance value of said flash lamp.

[0027] The first strength level of the simmer current is within a range from about 10mA to about 100mA. The second strength level of the simmer current is within a range from about 1A to about 20A. The strength of the main discharge pulses is within a range between 100A and 1000A. Said first synchronization pulses and said second synchronization pulses are generated by the same generator, where the first synchronization pulses, which switch the simmer current from the first strength level to the second strength level are provided directly from the generator output and the second synchronization pulses, which trigger the main discharge pulses are provided from the generator output via a delay circuit with a delay equal to said time interval.

[0028] The method of the present invention is explained in more detail with a help of the accompanying drawings, wherein:

Fig. 1 is a block diagram illustrating a method of controlling the current of a flash lamp according to the first variant of the present invention.

Fig.2 is a waveform of the current strength during one operating cycle of the flash lamp.

Fig.3 shows a waveform of the flash lamp during multiple operating cycles and corresponding sequences of synchronization pulses.

Fig.4 shows other embodiments of the first variant of the present invention.

Fig.5 is a block diagram illustrating a method of controlling the current of a flash lamp according to the second variant of this invention.

Fig.6A and Fig.6B show time dependences of the flash lamp's voltage, current and resistance during the main discharge phase for two different simmer current levels.

Fig.7A and Fig.7B show a circuit of an exemplary constant-current source and its operation waveforms.

Fig.8 shows a circuit of a current source with a closed loop feedback for current strength real-time control depending on the flash lamp's resistance value.

[0029] According to the present invention, a gas-discharge lamp is repetitively pulsed by main current pulses and during time periods between flashes the lamp is being simmered. An exclusive feature of the method of this invention is that the simmer current strength has two levels. During the major part of the simmer phase, a first simmer current level I_0 is maintained which is extremely low, and immediately prior to the main current pulse a second simmer current strength level I_1 is switched on. According to the first variant of the present invention, the second simmer current strength level I_1 is about two orders of magnitude higher than the first simmer current level I_0 and is determined in advance. According to the second variant of the present invention, the second simmer current strength level I_1 is controlled in a real time to attain a predetermined value of lamp's resistance.

[0030] Referring to Fig.1 the flash lamp 1 is driven by three current sources (2, 3, 4): a first simmer current source 2, a second simmer current source 3 and a main discharge current source 4. Operation of the current sources is strictly synchronized with the help of a synchronization system, comprising a generator of initial synchronization pulses 5 and a delay line 8, which together provide sequences of synchronization pulses (6, 7). The first simmer current source 2 is switched on once per lamp's operation. The second simmer current source 3 and the main discharge current source 4 provide trains

of current pulses the occurrences of which are triggered by synchronization pulses 6 and 7, respectively.

[0031] After the flash lamp 1 is being ignited, the first simmer current source 2 is switched on and is set to provide a constant-level I_0 current which is the lowest possible simmer current that still ensures that a discharge does not get extinguished. Although the arc is highly unstable, the current flow is maintained. It was empirically determined that for a typical 4mm bore diameter flash lamp 50mA is enough to keep the lamp simmering. And that is about ten times less than the simmer current strengths used in the art (line 10 in Fig.2). For flash lamps with other parameters the strength level I_0 of the simmer current necessary to maintain the arc varies from about 10mA to 100mA. A particular value of this first simmer current strength level I_0 is determined before using a flash lamp in a system.

[0032] At the very end of the simmer phase the second simmer current source 3 is switched on. It generates a short current pulse with the amplitude needed to increase the current flowing through the flash lamp 1 to achieve the second simmer current strength level I_1 . As was explained before, increasing a current strength stabilizes a direction of the discharge channel and enlarges its diameter. At some particular current strength value ionized gas (plasma) gets expanded to fill the whole tube of a flash lamp. The second strength level I_1 of the simmer current strength is selected so that plasma uniformly fills an entire volume of the lamp. A wall-stabilized plasma has low fluctuations. Depending on flash lamp's parameters, the strength of the current that is sufficient to uniformly fill the lamp falls within a range from about 1A to about 20A. For a typical 4mm diameter flash lamp $I_1 = 5A$. Thus, the first level and the second level of the simmer current strength differ by two orders of magnitude.

[0033] The simmer phase is followed by the main discharge phase. The main discharge current source 4 provides a short current pulse with high amplitude resulting in an intense current flow of the strength I_2 inside the flash lamp 1. Depending on the flash lamp parameters, the strength of the main discharge current is in a range between 100A and 1000A. For a typical 4mm diameter flash lamp $I_2 = 500A$.

[0034] Thus, the method of this invention comprises a control of the flash lamp current to have three strength levels: I_0 , I_1 and I_2 . At transition from the first strength level I_0 to the second strength level I_1 of the simmer current and from the second strength level I_1 of the simmer current to the main discharge current strength level I_2 the lamp experiences current strength changes by two orders of magnitude. Duration of the main discharge current pulse is equal to 150 μ s, which in Fig.2 is denoted as t_2 . Duration of the second simmer current level phase t_1 depends on lamp's parameters and concrete strength values of I_0 , I_1 and also on a time constant required for the lamp to achieve strength level I_1 . Preferably, t_1 is set to be equal to said time constant required for the lamp to achieve strength level I_1 . It varies within a range from

100 μ s to 500 μ s. For $I_0 = 50$ mA and $I_1 = 5$ A current levels supplied to the lamp, t_1 is approximately equal to 150 μ s. Duration of the first simmer current level phase depends on a pulse repetition rate f of the main current pulses and the durations of other phases as follows: $(1/f - t_1 - t_2)$.

[0035] The pulse of the second simmer source 3 is triggered by the first synchronization pulse 6, while the pulse of the main discharge source 4 is triggered by the second synchronization pulse 7. As mentioned above, both sequences of synchronization pulses originate from a single sync pulse generator with a frequency f preselected by the user. The output of said sync pulse generator is a train of pulses 5 which is then divided into two sequences of synchronization pulses 6 and 7, then a delay line 8 shifts in time the train of pulses 7 by said time interval t_1 (see Fig.3). One operating cycle of the flash lamp is depicted in Fig.2. A waveform 9 of the current supplied to the lamp has three strength levels I_0, I_1, I_2 . Neither of simmer current strength levels (I_1 and I_0) coincides with the standard simmer current level 10. The simmer current of the first strength level I_0 ensures existence of the discharge channel at smallest consumption of the lamp. The simmer current of the second strength level I_1 prepares the flash lamp for the next phase. The main discharge occurring in a totally filled lamp has low fluctuations of current and optical radiation. After the main discharge phase, the lamp returns to the first strength level of the simmer current. Time intervals t_1 and t_2 which are of similar durations are short compared with the duration of the operating cycle.

[0036] In Fig.3 a time dependence 11 of the current flowing through the flash lamp 1 during multiple operating cycles and corresponding sequences (12, 13) of synchronization pulses (6, 7). Starting from a moment 14 of lamp's ignition current is continuously supplied to the lamp 1 (a zero-level current is denoted as a line 15). The waveform 11 of current is comprises a step-alike function 9 of Fig.2. At the beginning of each operating cycle (e.g., point 16) the as-low-as-possible current of the strength level I_0 is continuously supplied by the first simmer current source 2. It continues until a moment (e.g., 17) when the first synchronization pulse 6 arrives to the second simmer current source 3 or to some central controller of the system. The source 3 increases the strength of the current supplied to the lamp to attain a second level I_1 . After a time delay which equals to t_1 , the second synchronization pulse 7 triggers delivery of a current pulse from the main discharge current source 4 and at the same time the second simmer current source 3 is switched off. After a time interval t_2 (and time for intense discharge to completely relax) the supply of the current from the current source 4 ends, and the lamp starts a new cycle.

[0037] Further, there may not be three physically separate current sources. Alternatives for the embodiment shown in Fig.1 might be apparent for those skilled in the art. For example, Fig.4 illustrates the case when a current supply system comprises two current sources: a simmer current source 19 with a two-level output and the main

discharge current source (4). Further, the current supply system may comprise a single block (20). The time dependences provided by sources 19 and 4 or a block 20 coincide with waveforms 9, 11 of Fig.2 and Fig.3.

[0038] In Fig.5 the second variant of the method of this invention is disclosed. Herein, a closed feedback loop is incorporated for adjusting the second strength level I_1 of the simmer current in accordance with lamp resistance. It is the aim to attain a predetermined value of resistance prior to the main discharge phase. Therefore, an instantaneous lamp resistance value is being measured and the strength of the simmer current is controlled in a real time.

[0039] Analogously to the previous embodiments, during the major part of any operating cycle the flash lamp is fed by the low-level I_0 simmer current. With the synchronization pulse 6 the current supply system 20 or its equivalents are triggered to begin increasing the simmer current. A controller 21 is engaged to measure a current flowing through the flash lamp 1 and a voltage between its electrodes. From the measured instantaneous values of current strength and voltage, instantaneous resistance values are calculated.

[0040] The strength of the simmer current is being increased until the lamp resistance attains some predetermined value. After attaining it, the controller 21 sends a command to the current supply system 20 or its equivalent to stop increasing the simmer current. This increased level I_1 of the simmer current is maintained until the beginning of the main discharge phase which begins with the synchronization pulse 7. The synchronization pulse 7 triggers the generation of the main discharge current pulse with the strength I_2 while at the same time the controller 21 is switched off.

[0041] The time interval for the lamp to attain resistance equal to said predetermined resistance value depends on the characteristics of the simmer current supply and parameters of the flash lamp. Also, for some reasons the rate of lamp resistance change may vary from cycle to cycle. Therefore, t_1 is chosen to be slightly longer than the empirically determined duration necessary to achieve the desired lamp resistance. Doing this, the predetermined lamp resistance is achieved at every cycle despite some fluctuations.

[0042] Said predetermined resistance value is estimated from the voltage time dependence during the main discharge period. There is a strong correlation between a value of lamp resistance at the end of simmering and evolution of the main discharge. If the main discharge begins when a flash lamp is in condition of high resistance, the voltage waveform has two maxima: it is high at the beginning of the main discharge phase, then it decreases and further it grows and decays (see Fig.6A). This form of voltage time dependence curve is undesirable because of output radiation instability, and also because of electromagnetic noise. If at the beginning of the main discharge phase a flash lamp is already in a low-resistance condition the voltage evolves more evenly:

initially, it grows, after that decreases (see Fig.6B).

[0043] Drawings Fig.6A and Fig.6B show time dependences of voltage, current and resistance for a typical 4mm diameter and 75mm length flash lamp. If immediately prior to the main discharge phase a strength of the simmer current is $I_1=0,05A$, the initial lamp resistance is equal to 140 ohms (Fig.6A). For $I_1=10A$, resistance is equal to 4 ohms (Fig.6B).

[0044] Against, increasing the simmer current at the very end of the simmer phase prepares the flash lamp to the main discharge. The discharge channel is formed and stabilized when the time dependence of lamp's voltage at the main discharge phase is similar to the one illustrated in Fig.6B.

[0045] A proper value of lamp's resistance is selected so that the voltage waveform in the main discharge begins with monotonic growth. Moreover, resistance is a more universal parameter because it is as much the same for various flash lamps and it is somewhere around 4 ohms. Whereas the simmer current strength value for which the voltage waveform is good, strongly depends on lamp parameters. For example, it is enough 4 amperes for 3mm diameter lamp, while for 4mm lamp 5 amperes, and for 5mm lamp simmer current levels from 8 to 10 amperes are necessary.

[0046] In order to employ the first variant of the present invention, a current strength value needed for the lamp to be uniformly filled with plasma must be predetermined. This is done on a special test bench where one can visually monitor the arc form. Since characteristics vary from lamp to lamp and also deteriorate in time, it is recommended to set the value I_1 about 10 or 20 per cent higher than that experimentally estimated. While for the second variant of the present invention, regardless of a more complex circuitry, selection of the second level simmer current strength I_1 occurs independently of changes of lamp characteristics.

[0047] Fig.7A is an exemplary scheme of a current source which is able to provide a selected value of the current strength. Such type of a constant-current supply may be used as the first simmer current source 2 and the second simmer current source 3 in the system of Fig. 1 (with different component parameters). It comprises a DC voltage source 22, a current summation diode 23, an inductor 24, a switch 25, a current measurement resistor 26, an inverse-biased diode 27, an RS trigger 28, a comparator 29 and a clock-pulse generator 30.

[0048] A working principle of the current source shown in Fig.7A can be understood from diagrams of Fig.7B. Therein these waveforms are shown: gating signal 31 and output signals 32-34 of the pulse generator 30, comparator 29 and RS trigger 28, respectively, as well as a time dependence 35 of a current flowing through the flash lamp 1.

[0049] Initially (time moment $t = 0$) all the signals are OFF. The switch 25 is closed and there is no current flow through the flash lamp (1). When the gating signal 31 is switched ON, the clock-pulse generator 30 is enabled,

its first pulse sets RS trigger 28 ON thus opening the switch 25. The current starts to flow from the DC source 22 through the flash lamp 1, diode 23, inductor 24, switch 25 and resistor 26 and back to DC source 22. The growth rate of the current is limited by inductance of the inductor 24.

[0050] The strength of the current in the circuit is calculated from a voltage drop across the resistor 26, and, further, with the help of a comparator 29 is compared with a preset current value I_{set} . When the current strength in the circuit reaches said preset current value I_{set} , the comparator 29 resets the RS trigger 28, therefore, the switch 25 closes. Now the current flow is maintained by the energy stored in the inductor 24 and flows through the diode 27, flash lamp 1 and diode 23. The strength of the current inside the flash lamp 1 slowly decreases until a next pulse of the clock-pulse generator 30 starts a new cycle. A clock-pulse frequency f_1 is a parameter that governs a precision of a current level maintained by the current source of Fig.7A.

[0051] The gating signal 31 is provided by some controller (not shown in the scheme of Fig.7A). If the current source of Fig.7A is employed as the first simmer current source 2 of Fig.1, ON/OFF states of the gating signal 31 correspond to the START/END of lamp's operation. For the second simmer current source 3, the gating signal 31 is ON at time intervals from a moment the first synchronization pulse 6 arrives until a moment the second synchronization pulse 7 arrives.

[0052] Fig.8 shows an example of a current source scheme which is suitable the second variant of the present invention. Herein, the simmer current must be provided for which resistance of the flash lamp becomes equal to a predetermined resistance value R_{set} . Voltage and current are measured in a real time. Using these data a microcontroller 21 calculates an instantaneous value of lamp's resistance and compares it with the predetermined resistance value R_{set} which is set at microcontroller 21. Until resistance of the flash lamp 1 is high, the switch 25 is kept open, and lamp's current is growing. As soon the lamp's resistance achieves R_{set} value, the microcontroller 21 sends a command to the RS trigger 28 to close the switch 25 and, therefore, to stop the growth of lamp's current. A further sequence of commands to maintain the flash lamp's resistance constant is analogous to the one described above for maintaining constant current (see description of Fig.7B).

[0053] Schemes of Fig.7A and Fig.8 are given by way of illustration and example only and thus are not limitative of the present invention.

[0054] Advantages of the present invention are readily apparent from the comparison of the charge flowing through the lamp during simmering. At 10Hz pulse repetition rate, charge that flows through the 4mm flash lamp during the simmer phase is equal to: 50mC with the widely used 0.5A simmer current and only 6mC with the two-simmer-current-level approach of this invention. Charge values for other pulse repetition rate values are:

50Hz - 10mC and 1.7mC; 100Hz - 5mC and 1.5mC; 200Hz - 2.5mC and 1mC for standard and proposed approaches, respectively. Since the charge of the main discharge phase is about $500A \times 150\mu m = 75mC$, lamp's consumption is much the same for the simmer and the main discharge phases in the standard approach. The method of this invention allows for reducing the charge that flows through the flash lamp during the simmer mode from 2.5 to 8 times. The lamp's service life is extended less because it is also dependent on other parameters. At 50Hz pulse repetition rate the service life of the 4mm flash lamp can be extended approximately twice.

[0055] Moreover, the extension of lamp's service life is attained without sacrificing the stability. The method of this invention ensures that plasma is uniformly distributed inside the flash lamp, also voltage and current fluctuations relax prior to each of the main discharge pulses. Therefore, output light pulses produced by the flash lamp driven according to the method of this invention are characterized by high energy stability and low time jitter. It is also possible to have the same service life and stability for flash lamps with differing parameters as well as for a single lamp degrading in time. For different lamps, it is done by selecting appropriate levels of simmer current. For a single lamp, parameters of which change in time, it is possible to achieve a long-term output radiation stability by repeatedly adjusting simmering conditions.

[0056] Another advantage of this invention relates to flash-lamp-pumped lasers. Electrical energy conversion into inversion of the gain medium is more efficient when a simmer current immediately prior to the main discharge is higher. For a 4mm diameter and 75mm length flash lamp the inversion accumulation efficiency is equal to 78% of the flash lamp discharge energy as modelled with $I_{\text{simmer}}=0.5A$, and 80% with $I_{\text{simmer}}=5A$.

[0057] Therefore, the method of this invention allows for increasing laser output energy and improving energy and temporal stability. Furthermore, low time jitter ensures a more reliable laser operation at Q-switching regime. Also it is important for synchronization of laser pulses with a work piece movement.

[0058] All the given illustrations are possible but not limiting realizations of the present invention. Accordingly, the scope of protection is disclosed in the appended claims.

Claims

1. Method of controlling the current of a flash lamp when main discharge pulses of a current are delivered to the flash lamp causing an intense gas discharge, where the main discharge pulses are triggered by synchronization pulses, while during the time intervals between said main discharge pulses the flash lamp is supplied with a continuous simmer current, a strength of which is increased prior to delivering each of said main discharge pulses **characterized**

by the following steps:

during the major part of time interval between adjacent main discharge pulses a strength of the simmer current is maintained at a first level (I_0), which is as low as possible while still ensures an existence of the discharge channel, whereas prior to supplying each of said main discharge pulses, a first synchronization pulse switches the simmer current to a second strength level (I_1), which is higher than said first strength level (I_0), the second strength level (I_1) depends on the flash lamp parameters and is equal to the lowest possible current strength level that is sufficient to ensure that the tube of said flash lamp is entirely and uniformly filled with plasma, further, a second synchronization pulse, which is delayed with respect to said first synchronization pulse by a predetermined time interval (t_1), triggers the main discharge pulse, whereas said predetermined time interval (t_1) is the shortest possible time interval for the flash lamp to be entirely and uniformly filled with plasma.

2. Method of controlling the current of a flash lamp when main discharge pulses of a current are delivered to the flash lamp causing an intense gas discharge, where the main discharge pulses are triggered by synchronization pulses, while during the time intervals between said main discharge pulses the flash lamp is supplied with a continuous simmer current, a strength of which is increased prior to delivering each of said main discharge pulses

characterized by the following steps:

during the major part of time interval between adjacent main discharge pulses a strength of the simmer current is maintained at a first strength level (I_0), which is as low as possible while still ensures an existence of the discharge channel, whereas prior to delivering each of said main discharge pulses, a first synchronization pulse triggers increasing of the simmer current strength until flash lamp's resistance achieves a predetermined resistance value, which depends on the flash lamp parameters and is equal to a resistance with which the main discharge phase in said flash lamp begins with a voltage growth, further, a second synchronization pulse, which is delayed with respect to said first synchronization pulse by a predetermined time interval (t_1), triggers the main discharge pulse, whereas said predetermined time interval (t_1), is the shortest

possible time interval to achieve said predetermined resistance value of said flash lamp.

- 3. Method of controlling the current of a flash lamp according to claim 1 or claim 2 **characterized in that** the first strength level (I_0) of the simmer current is within a range from about 10mA to about 100mA. 5
- 4. Method of controlling the current of a flash lamp according to any one of claims 1- 3 **characterized in that** the second strength level (I_1) of the simmer current is within a range from about 1A to about 20A. 10
- 5. Method of controlling the current of a flash lamp according to any one of claims 1- 4 **characterized in that** the strength (I_2) of the main discharge pulses is within a range between 100A and 1000A. 15
- 6. Method of controlling the current of a flash lamp according to any one of claims 1-5 **characterized in that** said first synchronization pulses and said second synchronization pulses are generated by the same generator, where the first synchronization pulses, which switch the simmer current from the first strength level (I_0) to the second strength level (I_1) are provided directly from the generator output and the second synchronization pulses, which trigger the main discharge pulses are provided from the generator output via a delay circuit with a delay equal to said predetermined time interval (t_1). 20
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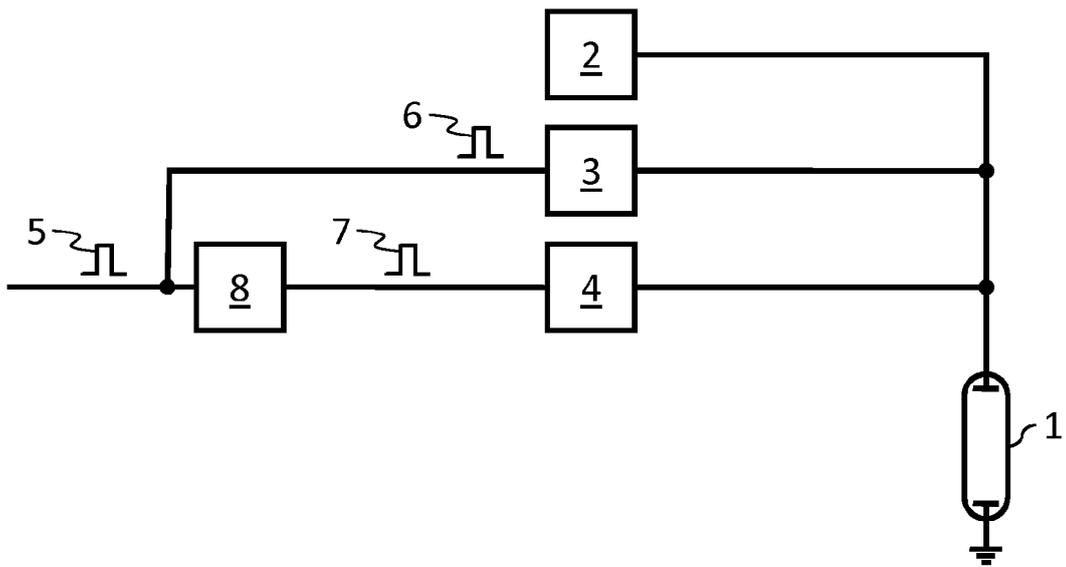


Fig.1

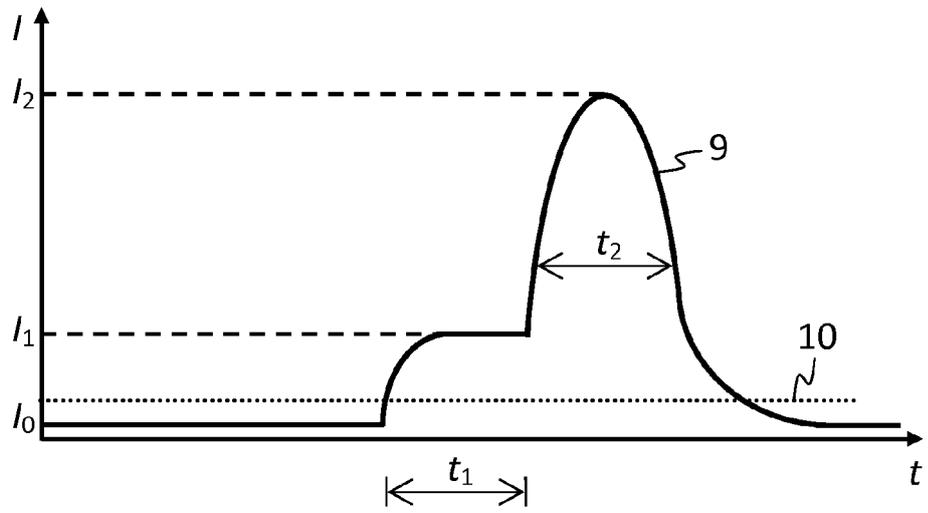


Fig.2

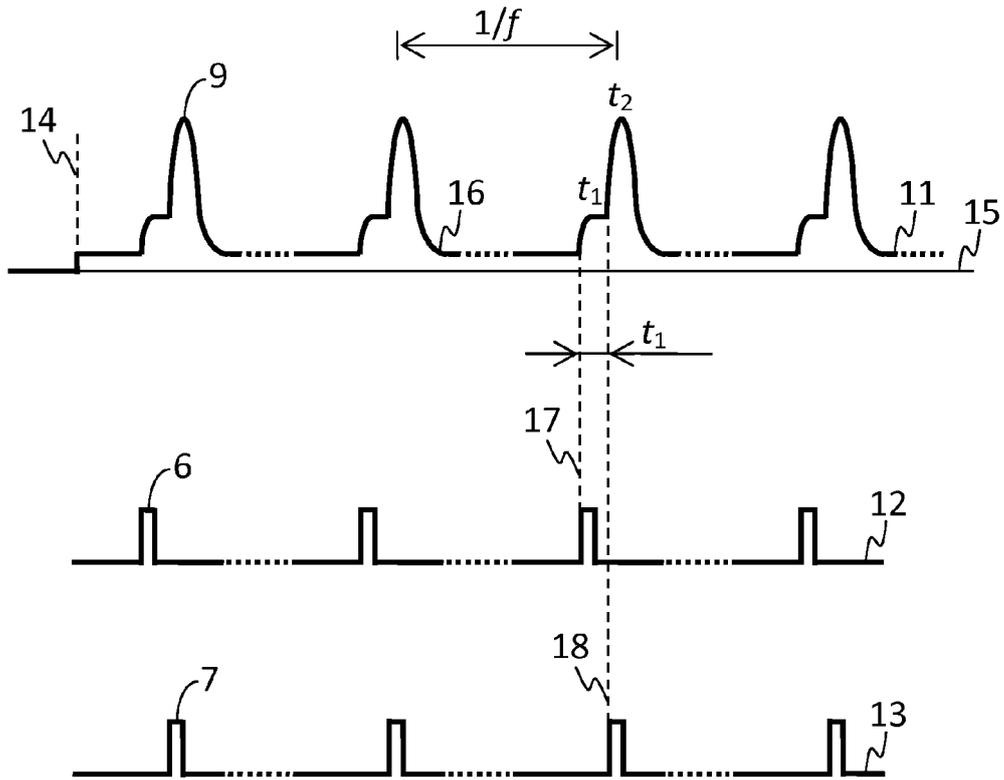


Fig.3

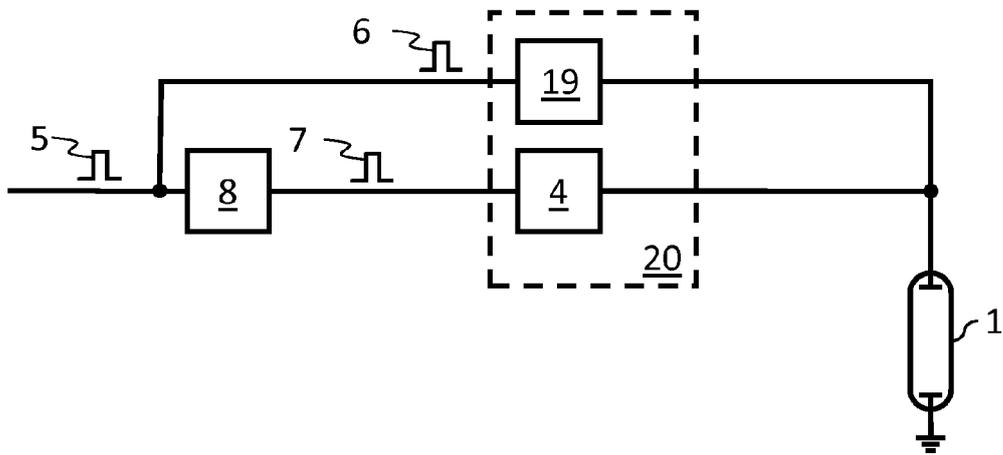


Fig.4

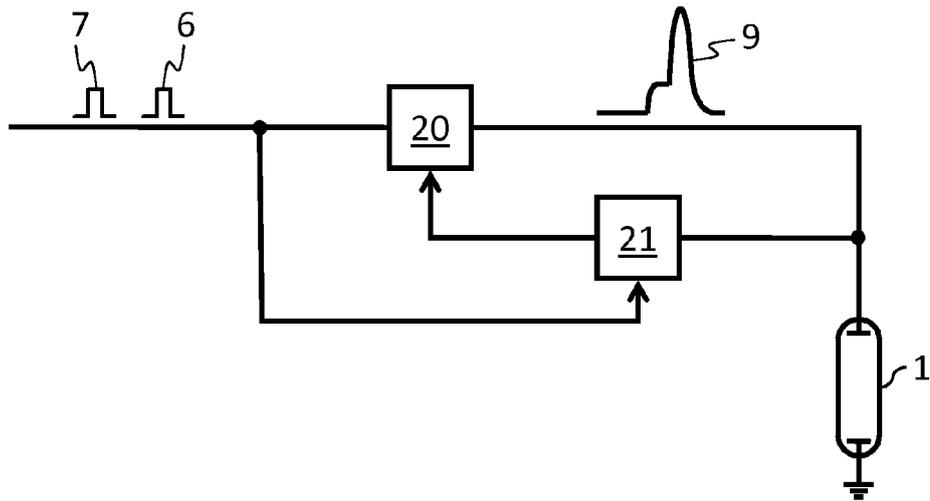


Fig.5

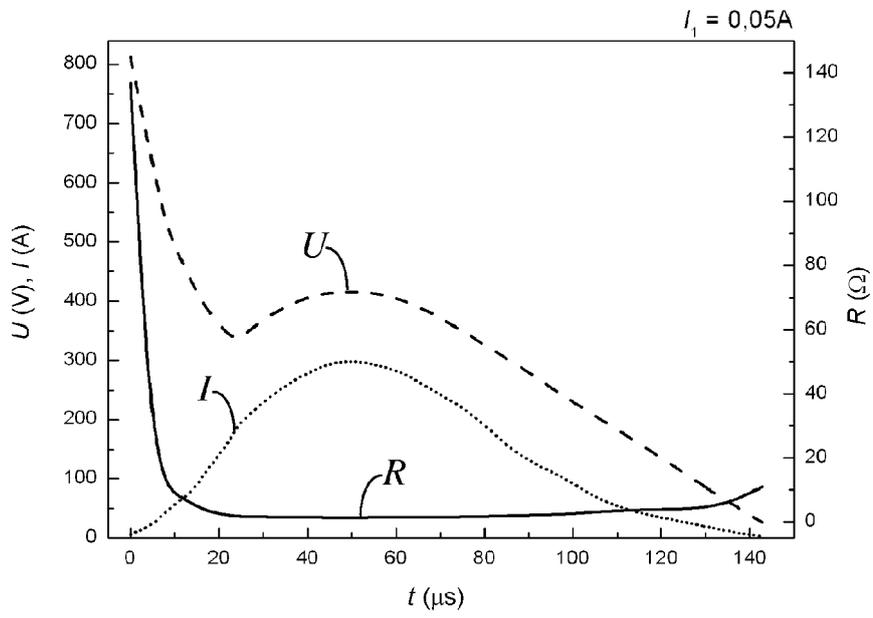


Fig.6A

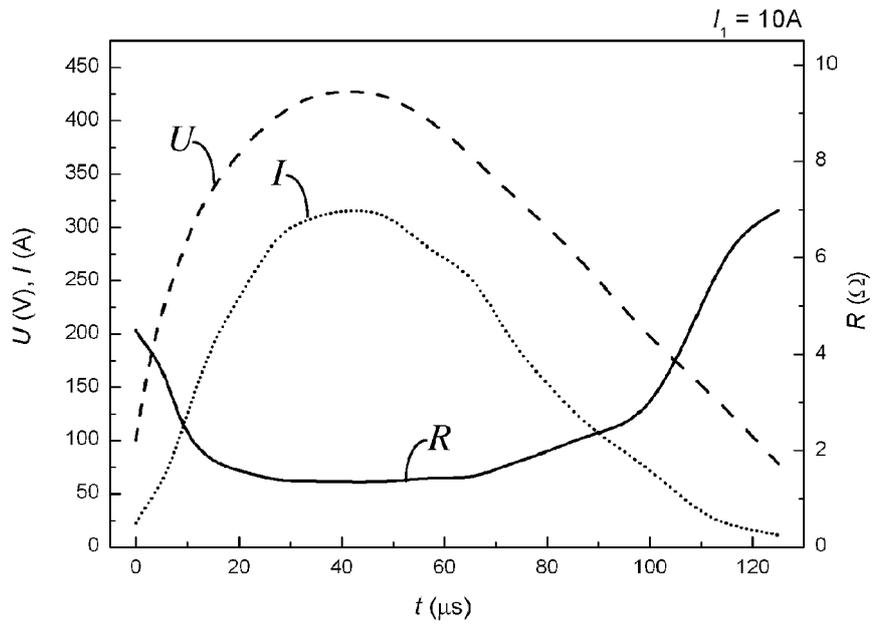


Fig.6B

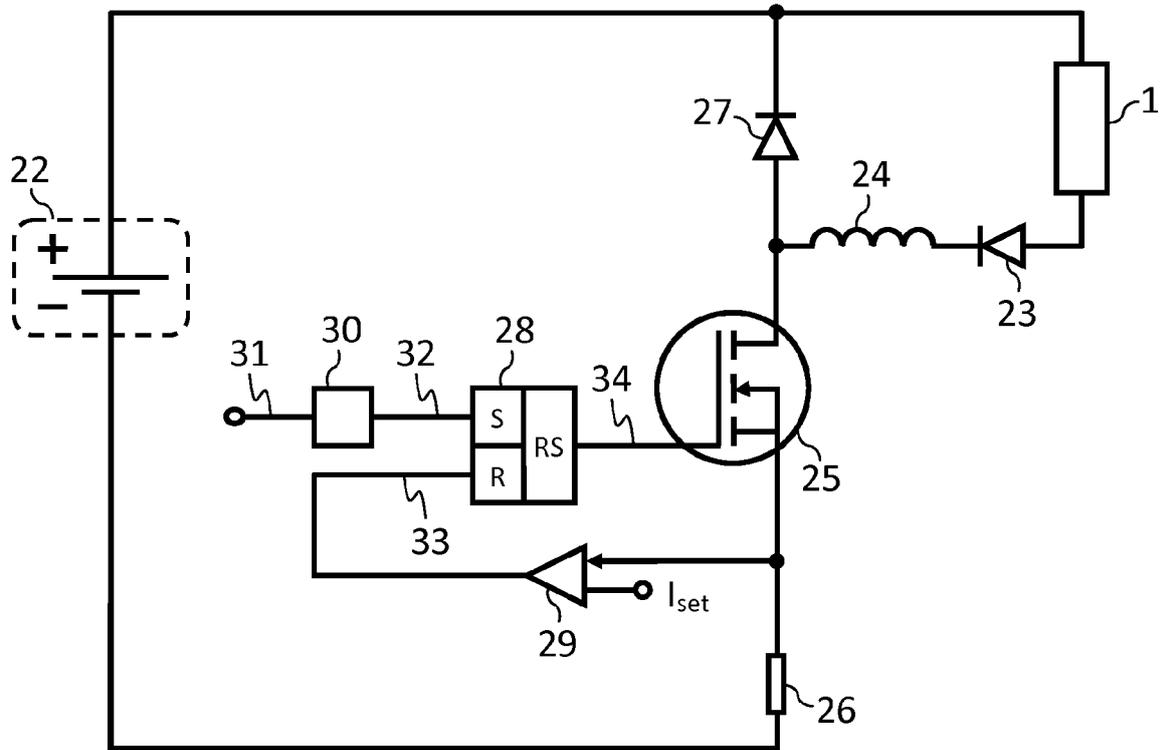


Fig.7A

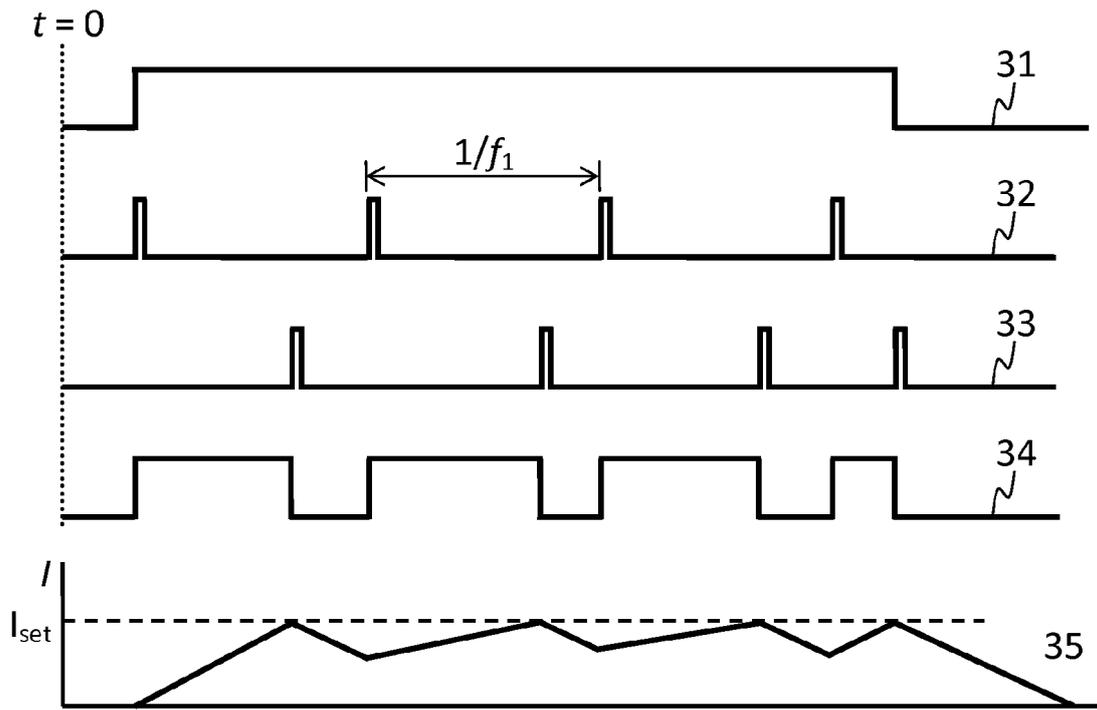


Fig.7B

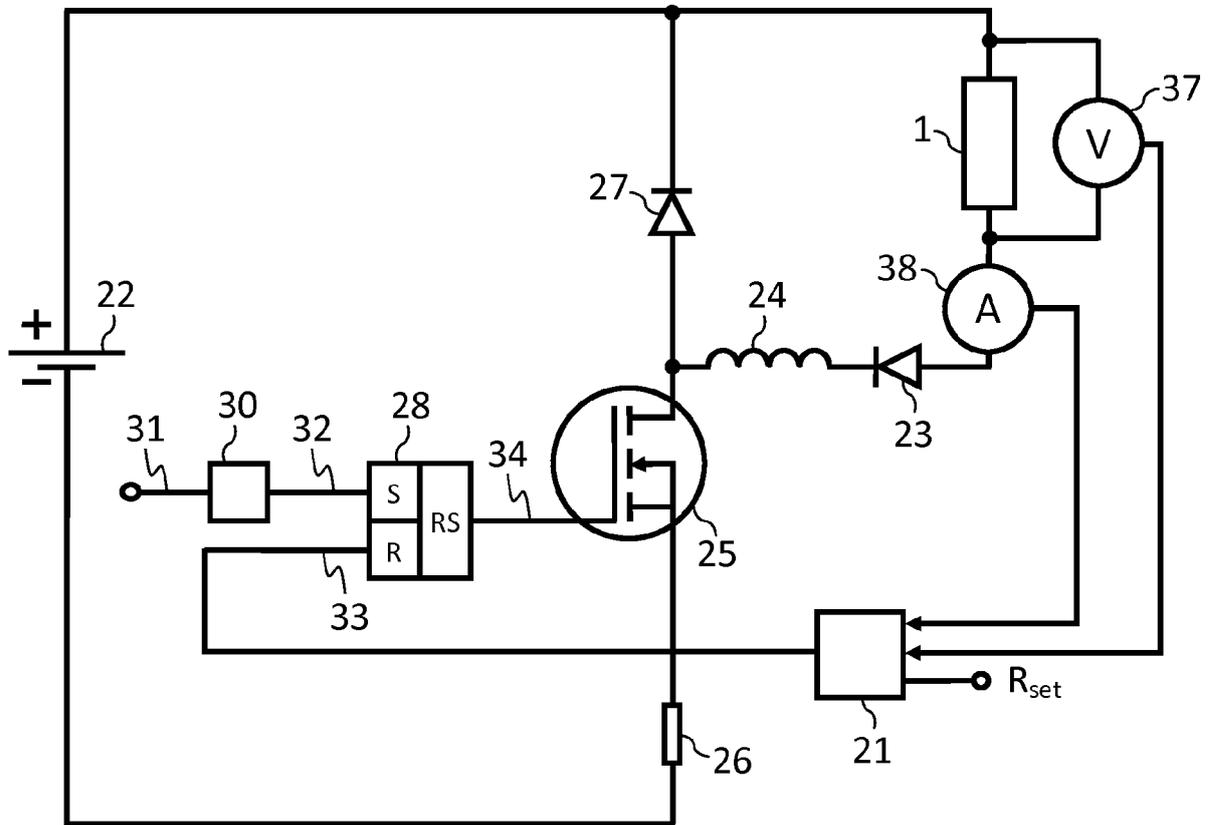


Fig.8



EUROPEAN SEARCH REPORT

Application Number
EP 12 19 7321

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