



- (51) **International Patent Classification:**
H02H 3/16 (2006.01) *H02H 3/08* (2006.01)
- (21) **International Application Number:**
PCT/CN2017/076671
- (22) **International Filing Date:**
14 March 2017 (14.03.2017)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
62/307,589 14 March 2016 (14.03.2016) US
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(81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) **Title:** CONTROL CIRCUIT AND HIGH FREQUENCY CIRCUIT BREAKER

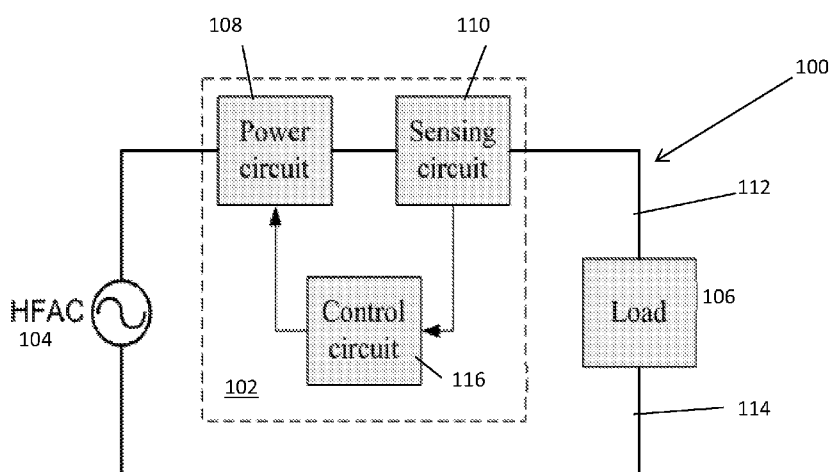


FIG. 1

(57) **Abstract:** A high frequency circuit breaker (HFCB) and a control circuit for a HFCB are provided. The HFCB includes a control circuit, a sensing circuit and a power circuit. The sensing circuit senses at least one of a high frequency leakage current and a high frequency current passing through a load and the power circuit connects and disconnects power to the load. The control circuit includes an analog comparator and a switched state retention circuit. The analog comparator compares an output from the sensing circuit to a current reference and the switched state retention circuit provides a control signal to the power circuit based on an output from the analog comparator, to force the power circuit to selectively connect or disconnect power to the load.

CONTROL CIRCUIT AND HIGH FREQUENCY CIRCUIT BREAKER

PRIORITY CLAIMS

[0001] The present application claims priority to United States of America provisional patent application number 62/307,589.

TECHNICAL FIELD

[0002] The following discloses a control circuit for a circuit breaker, and a circuit breaker incorporating that control circuit. In particular, a control circuit and a circuit breaker are disclosed for monitoring current in a high frequency alternating current system.

BACKGROUND

[0003] In many modern systems it is desirable to use high frequency alternating current (AC) electrical distribution. Such systems are employed in space stations, electric vehicles, renewable energy micro-grids, telecommunications systems and computer systems. High frequency AC operates at 20-50 kHz and has many potential benefits including enabling use of compact, high frequency transformers, facilitating a considerable reduction in the amount and volume of electrical components, and improving dynamic response, degradation and elimination of acoustic noise.

[0004] In normal circumstances, the energized (live) wire(s) and the return (neutral) wire are expected to carry the same current. Any difference usually indicates that an electrical anomaly is present. This difference is called the residual-current or leakage current.

[0005] Even a small leakage current creates a risk of harm or death from electric shock if the leakage current passes through a human. A leakage current of around 30 mA passing through a human is potentially sufficient to cause cardiac arrest or serious harm if it persists for more than a small fraction of a second.

[0006] As systems become more complex, and as they age and degrade, the likelihood of leakage current can increase. To reduce the risk of injury from leakage current a residual-current device (RCD), or residual-current circuit breaker (RCCB), is installed in electrical circuits to quickly disconnect current and thereby prevent serious harm from extended electric shock.

[0007] Due to the fast response of high frequency AC, conventional low frequency residual-current circuit breakers are not suitable for use in high frequency AC systems. However, the design of high frequency AC circuit breakers that can reliably operate, and respond quickly to changes leakage current, has been a challenging problem.

SUMMARY OF INVENTION

[0008] The present disclosure provides a control circuit for a high frequency circuit breaker (HFCB), the HFCB comprising a sensing circuit for sensing at least one of a high frequency leakage current and a high frequency current passing through a load, and a power circuit for connecting and disconnecting power to the load, the control circuit comprising:

- a analog comparator for comparing an output from the sensing circuit to a current reference; and

- a switched state retention circuit for providing a control signal to the power circuit based on an output from the analog comparator, to force the power circuit to selectively connect or disconnect power to the load.

[0009] The control circuit may be for a HFCB the sensing system of which senses high frequency residual current. The control circuit may be for a HFCB the sensing system of which senses high frequency current (i.e. load current). The control circuit may be for a HFCB the sensing system of which senses high frequency residual current and high frequency current.

[0010] The output of the analog comparator may be based on a difference between the output from the sensing circuit and the current reference.

[0011] The output from the sensing circuit may comprise a voltage, the current reference comprises a voltage indicative of a threshold current, and the analog comparator identifies a

voltage differential. The threshold current may be the threshold leakage current. The threshold current may be the threshold load current. The sensing circuit may sense both leakage current and load current and the comparator may identify the voltage differential between each current and its respective threshold.

[0012] The analog comparator may comprise a high speed comparator integrated circuit (IC).

[0013] The analog comparator may comprise a differential operational amplifier (OpAmp) for determining a difference between the output from the sensing circuit and the current reference. The OpAmp and the current reference may be driven by a common direct current (DC) input voltage.

[0014] The current reference may comprise a variable impedance and an impedance, and changing an impedance of the variable impedance adjusts the current reference.

[0015] The output from the analog comparator may have multiple states. In particular, the output from the analog comparator may have a first state indicating the output from the sensing circuit does not exceed the current reference, and a second state indicating the output from the sensing circuit exceeds the current reference.

[0016] The control signal from the switched state retention circuit may have multiple states. In particular, the control signal from the switched state retention circuit may have a first control state for forcing the power circuit to connect power to the load and a second control state for forcing the power circuit to disconnect power to the load. The control signal may switch from the first control state to the second control state once the output from the analog comparator switches from the first state to the second state. When the control signal attains the second state it may maintain the second state regardless of changes in the output from the analog comparator.

[0017] The control circuit may further comprise a reset switch activation of which forces the switched state retention circuit to the first state if the output of the analog comparator is in the first state.

[0018] The switched state retention circuit may comprise a not-OR (NOR) circuit comprising multiple NOR gates and an inverter circuit comprising multiple inverters. Two of the NOR gates may be used to maintain the second state of the switched state retention circuit, where:

- each of the two NOR gates provides an input to the other;
- an input of the two NOR gates is affected by activation of the reset switch; and
- an input of the other of the two NOR gates is affected by output of the analog comparator change from the first state to the second state.

[0019] The present disclosure also provides a high frequency circuit breaker (HFCB) comprising a control circuit as described above. This may be a HFCB comprising:

- a control circuit;
- a sensing circuit for sensing at least one of a high frequency leakage current and a high frequency current passing through a load; and
- a power circuit for connecting and disconnecting power to the load,

wherein the control circuit comprises:

- an analog comparator for comparing an output from the sensing circuit to a current reference; and
- a switched state retention circuit for providing a control signal to the power circuit based on an output from the analog comparator, to force the power circuit to selectively connect or disconnect power to the load.

[0020] The power circuit may comprise a relay and a switch each of which is switchable between an ON state and an OFF state. The relay and switch may be in series such that if either one of the relay and switch switches to the OFF state, power is disconnected to the load. The relay and switch may alternatively be in parallel such that power is connected to the load once either one of the relay and switch is switched to the ON state.

[0021] Some embodiments provide of the present circuit breaker enable one or both of:

- (i) high frequency AC current to be disconnected within a specified duration – e.g. 40ms – if the detected high frequency leakage current is more than a specified root-mean-square (RMS) value – e.g. 30 mA; and

- (ii) high frequency AC current to be disconnected quickly if the detected high frequency load current is more than the specified current value. This can occur in the event of an overload or short-circuit.

[0022] Thus some embodiments may provide a high frequency residual-current circuit breaker with overcurrent (excessive load current) protection (HFRCCBO). This is a device for quickly disconnecting current to prevent serious harm from an ongoing electric shock and to protect against overheating or fire risk due from short circuits or overcurrent resulting from an overloaded circuit. The present HFRCCBO can provide leakage current protection and overload or short-circuit protection in high frequency AC systems.

[0023] In some embodiments, the specified leakage current and/or the specified load current can be flexibly adjusted to suit a particular application.

[0024] The control circuit as described above, wherein the control circuit is for receiving an output from a sensing circuit comprising:

a first high frequency current transducer for sensing a load current and leakage current;
and

a second high frequency current transducer for sensing the other of the load current and leakage current; and

the control circuit comprises:

a first sub-circuit comprising:

the comparator, being a first comparator, for comparing an output from the first high frequency current transducer to a respective load current reference or leakage current reference; and

the switched state retention circuit, being a first switched state retention circuit;
and

a second sub-circuit comprising:

a second analog comparator for comparing an output from the second high frequency current transducer to a respective load current reference or leakage current reference; and

a second switched state retention circuit for providing a control signal to the power circuit based on an output from the second analog comparator, to force the power circuit to selectively connect or disconnect power to the load.

[0025] The sensing circuit may comprise a DC residual-current transducer and two AC-DC rectifiers. The power circuit may comprise two outputs, the load may comprise two terminals and the AC-DC rectifiers may each include an input, wherein one output of the power circuit and one terminal of the load provide an AC input to one of the two AC-DC rectifiers, and the other output of the power circuit and the other terminal of the load provide the other AC input to the other of the two AC-DC rectifiers. Each AC-DC rectifier may comprise a DC output and a difference between the DC outputs provides an input of the DC residual-current transducer, and an output of the DC residual-current transducer is isolated with the input of the DC residual-current transducer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0001] Some embodiments of the present invention will now be described, by way of non-limiting example only, with reference to the accompanying drawings in which:

[0002] FIG. 1 is a block diagram of a high frequency circuit breaker in accordance with the present disclosure;

[0003] FIG. 2a is a schematic diagram of a high frequency residual current circuit breaker with overcurrent protection (HFRCCBO) that provides quick disconnection;

[0004] FIG. 2b depicts the schematic structure of a HFRCCBO for providing quick connection and low conduction loss;

[0005] FIGs. 3a and 3b are schematic diagrams of power and sensing circuits, with FIG. 3a employing a high frequency residual current transducer and FIG. 3b employing a DC leakage current transducer;

[0006] FIG. 3c depicts the AC power supply voltage, circuit breaker control voltages, load voltage and load current for the circuits of FIGs. 3a and 3b;

[0007] FIG. 4 is a schematic diagram of a high frequency residual-current circuit breaker with overcurrent protection (HFRCCBO);

[0008] FIG. 5 is a schematic diagram of a control circuit divided into three sub-circuits – control circuits A, B and C;

[0009] FIG. 6a illustrates an embodiment of Control circuit A of FIG. 5;

[0010] FIG. 6b depicts the typical waveforms expected through Control circuit A of FIG. 6a;

[0011] FIG. 7a illustrates an embodiment of Control circuit B of FIG. 5;

[0012] FIG. 7b depicts the typical waveforms expected through Control circuit B of FIG. 7a;

[0013] FIG. 8a illustrates an embodiment of Control circuit C of FIG. 5;

[0014] FIG. 8b depicts the typical waveforms expected through Control circuit C of FIG. 8a;

[0015] FIG. 9 depicts the typical waveforms exhibited by a high frequency AC circuit employing a high frequency circuit breaker (HFCB) as described herein.

DETAILED DESCRIPTION

[0016] In a broad sense, the present disclosure provides control circuits and circuit breakers, each circuit breaker including at least one:

- control circuit;
- power circuit; and
- sensing circuit.

[0017] The circuit breakers are high frequency circuit breakers (HFCBs) in that the control circuit can operate at high frequency and can be used to create rapid control signals for connecting and disconnecting a high frequency AC power supply from a load.

[0018] In some embodiments, the power and sensing circuits may not be supplied and only the control circuit is provided. The control circuit may then be coupled with the various power circuits and sensing circuits to provide desired functionality. The control circuit employs no micro-controller unit (MCU). Instead, it is composed entirely from analog and logic components. In being entirely analog and logic, the control circuits shown herein provide fast detection and fast disconnection in the face of leakage and/or overcurrent. Also, in some embodiments the leakage current reference and/or the overcurrent reference can be changed flexibly depending on requirement. Thus the control circuits can be adjusted to detect current of a desired magnitude.

[0019] FIG. 1 provides a block diagram illustrating an embodiment of a circuit 100 comprising a high frequency residual-current circuit breaker 102. The circuit breaker 102 may also provide overcurrent protection.

[0020] HFAC 104 represents the high frequency AC supply for supplying power to the load 106 through the circuit breaker 102. The circuit breaker 102 comprises a power circuit 108, sensing circuit 110 and control circuit 116.

[0021] Power passes from the HFAC 104 through the power circuit 108, the power circuit 108 being used to connect and disconnect the high frequency AC supply 104 to the load 106 in the event of a detected leakage and/or overcurrent. The power circuit 108 consists of a relay/isolator and an electric switch. Each of the relay and switch is switchable between an ON (i.e. conducting) state and an OFF (i.e. non-conducting) state. These are actuated by the control circuit 116.

[0022] After passing through the power circuit 108, the power passes through the sensing circuit 110 and on to the load 106. The sensing circuit 110 detects one or both of load current and leakage current. The load current is detectable by detecting current only on the power energised wire 112. In contrast, the leakage current is the difference between current

delivered and current received from the load 106, and thus requires measurement of both the energised wire 112 and return wire 114.

[0023] The load and/or leakage current sensed by the sensing circuit 110 is then compared, using the control circuit 116, to a reference load and/or leakage current. The control circuit 116 determines whether any variation in current from the relevant reference current is within tolerable limits. If so, the circuit remains closed and power can continue to flow to the load. If the variation in current is outside tolerable limits, the control circuit 116 forces the power circuit 108 to disconnect power from the load.

[0024] The sensing circuit consists of one or more high frequency current transducers. The transducers can be used to detect one or both of leakage current and overcurrent, and thus can comprise one or both of a high frequency leakage current transducer and a high frequency overcurrent (or load current) transducer.

[0025] The sensor circuit transduces a detected current to a voltage output. That output is then sent to the control circuit.

[0026] The control circuit consists of analog components. It is used to compare one or both of the detected leakage current with the specified leakage current and the detected load current with the specified load current. Based on that comparison, the control circuit generates the control signals to force the power circuit to connect (including maintain connection) or disconnect power to the load. So as to be useable with small variations in current – e.g. where the threshold for tolerable leakage current is very small – the control circuit also amplifies the control signals to a level sufficient to drive a relay/isolator and/or an electric switch of the power circuit.

[0027] FIGs. 2a and 2b provide schematic structures of a high frequency residual current circuit breaker with overcurrent protection (HFRCCBO) 200, 200'. FIG. 2a illustrates the schematic structure enabling quick disconnection. This is achieved by providing a switch 228 and relay 226 in series. Thus switching either one of the switch 228 and relay 226 OFF will disconnect power from the load. FIG. 2b depicts the schematic structure enabling quick

connection and low conduction loss. This is achieved by providing switch 228' and relay 226' in parallel. Thus connection of either of the switch 228' and relay 226' will result in connection of power to the load, and resistance is lowered through the power circuit 224 when compared with series resistances.

[0028] Both FIGs. 2a and 2b provide a sensing circuit 202 that senses both leakage current and load current. This is to protect against overcurrent – i.e. excessive load current – and excessive current leakage. The sensing circuits 202 each comprise a high frequency leakage current transducer (HFLCT) 210 for sensing leakage current and a high frequency current transducer (HFCT) 212 for sensing load current.

[0029] Similarly, the control circuits 204 compare (i) a transduced voltage representative of the detected leakage current to a leakage current reference or specified leakage current 206 and/or (ii) a transduced voltage representative of the load current to a load current reference or specified load current 208. In some embodiments, the sensing circuit 202 may only sense one of the two currents and thus the control circuit 204 need only compare the sensed current against its reference 206, 208.

[0030] In general, the current references 206, 208 are each provided as a voltage for ready comparison to the voltage outputted by the sensing circuit 202 as a transduced quantity proportional to the relevant sensed current.

[0031] The current references 206, 208 are quantities (e.g. voltages) indicative of a respective current threshold. When the sensed current exceeds that threshold it triggers an overcurrent or leakage current event. The words “indicative of” are used since the design of the circuit may be such that (i) a sensed current equal to the threshold is the maximum permissible overcurrent or leakage current or, in the alternative, (ii) a sensed current equal to the threshold is the minimum, or lowest, current that will trigger overcurrent or leakage current protection. So both interpretations of “threshold” are intended to be covered by the words “indicative of”.

[0032] The control circuit 204 provides a comparator 214, 216 for each sensed current. The output of the respective comparator 214, 216 is designed to be HIGH or of HIGH level when the output of the respective comparator 214, 216 indicates that the relevant sensed current does not exceed its threshold indicated by the current reference. Conversely, a LOW output indicates the current is at least as high as the threshold. It will be appreciated, however, that a LOW or LOW level output may be similarly used to convey the same information and that, in such a case, the HIGH or LOW comparator outputs will need to be inverted before being inputted to the AND gate discussed below.

[0033] In normal conditions the load current is less than the specified load current 208. Consequently, the output of the high frequency current transducer (HFCT) 212 is less than the current reference 208. The output of the comparator 216 is therefore HIGH. The comparator 216 achieves this function by subtracting one voltage from the other. In other words, the comparator 216 may measure a voltage differential. The differential will be at least zero where the output of the HFCT 212 is at most equal to the current reference 208 resulting in a HIGH output – i.e. does not exceed the current reference 208 – and will be negative if the output of the HFCT 212 is greater than the current reference 208, resulting in a LOW output. The current reference in each case may alternatively be defined such the output is LOW if the sensed current is at least equal to the current reference and is otherwise HIGH.

[0034] Similarly, in normal conditions the leakage current is less than the specified leakage current 206. The output of the high frequency leakage current transducer (HFLCT) 210 is therefore less than the leakage current reference and hence the output of the comparator 214 is HIGH.

[0035] The present circuits 200 further include an ON/OFF switch 218. The ON/OFF switch 218 may be a manual switch used to commence delivering power to the load. For example, the ON/OFF switch 218 may be an ignition button of an electric vehicle. The output of the ON/OFF switch 218 is HIGH if the switch 218 is ON, and LOW if the switch 218 is OFF.

[0036] The outputs from each of the comparators 214, 216 and the ON/OFF switch 218 are delivered to an AND gate 220. Operation of the AND gate 220 will be understood by the skilled person.

[0037] Since normal conditions results in the output of the comparators 214, 216 and ON/OFF switch 218 being HIGH all three inputs to the AND gate 220 are HIGH. The output of the AND gate 220 is consequently HIGH.

[0038] In embodiments where the current is to be constantly delivered, an ON/OFF switch 218 may not be included. Also, as discussed above, some embodiments may only require one of the leakage current and load current to be sensed. In embodiments where no ON/OFF switch is required and only a single current is sensed, no AND gate will be necessary.

[0039] The output of the AND gate 220 may be delivered to an amplifier 222. This is most likely to be the case in circuits 200, 200' where the output of the AND gate 220 is insufficient to drive the power circuit 224. In cases where the output of the AND gate 220 is sufficient to drive the power circuit 224, no amplifier is needed.

[0040] In the embodiments shown, an amplifier 222 is present. The amplifier 222 amplifies the output of the AND gate 220 to a level capable of driving the power circuit 224 – in other words, to a level sufficient to actuate or drive relays and switches in the power circuit 224.

[0041] The power circuit 224, 224' includes a relay or isolator (Re) 226, 226' and an electric switch (Se) 228, 228'. The output of the amplifier 222 drives the relay or isolator (Re) 226, 226' and the electric switch (Se) 228, 228'. Thus Re 226, 226' is switched ON and Se 228, 228' is turned ON. Therefore, the high frequency AC power is supplied from supply 230 to load 232. Similarly, Re 226, 226' and Se 228, 228' are OFF and the high frequency AC current to the load 232 is disconnected if switch 218 delivers a stop instruction (OFF) or the output from one of the comparators 214, 216 is LOW.

[0042] Under abnormal operation conditions the output of the HFCT 212 and/or HFLCT 210 is more than the load current reference 208 and/or leakage current reference respectively. In other embodiments, an abnormal operation will be indicated by the output being at least equal to the current reference and/or leakage current reference. When the detected leakage current is more than the specified leakage current 206 the output of the comparator 214 is LOW.

Regardless of the output of comparator 216 or switch 218, the output of the AND gate 220 will be LOW and Re 226, 226' and Se 228, 228' switched OFF. The output of the comparator 214 maintains the LOW level to maintain leakage current protection.

[0043] The comparator 214 maintains the LOW level regardless of the output from the HFLCT 210, until the comparator 214 is reset by activating Reset 234. The Reset 234 resets the comparator 214 so that the output of the comparator 214 is once again dependent on the output of the HFLCT 210. If the output of the HFLCT 210 indicates the leakage current exceeds the leakage current reference 206, the output of the comparator 206 will again be driven LOW. Only once the HFLCT 210 indicates the leakage current does not exceed the leakage current reference 206 will the comparator output be HIGH.

[0044] Similarly, when the output of the HFCT 212 is more than the current reference 208 the output of the comparator 216 is LOW. The output of the AND gate 220 is thus also LOW and Re 226, 226' and Se 228, 228' are switched OFF. The output of the comparator 216 remains LOW to provide the overcurrent protection until Reset 236 is activated.

[0045] FIGs. 3a and 3b are schematic diagrams of power and sensing circuits. FIG. 3a employs a high frequency leakage current transducer (HFLCT). FIG. 3b employs a DC leakage current transducer (DCLCT).

[0046] In the power circuit 300 the relay (Re) 302 consists of a control coil 304 on circuit R_A-R_B, and two pole normally open contacts 306, 308 on circuits R_4-R_7 and R_6-R_9 respectively – circuit R_4-R_7 isolates a start switch 822 as discussed with reference to FIG. 8a.

[0047] Two pole normally open contacts 306, 308 are open if the DC voltage across the control coil 304 is 0 V, resulting from a LOW state of the output of the AND gate 220. Two pole normally open contacts 306, 308 are closed if the DC voltage across the control coil 304 is equal to the specified DC voltage (such as 12 V), resulting from a HIGH state of the output of the AND gate 220. Thus the relay 302 is capable of connecting and disconnecting the high frequency AC current.

[0048] The relay 302 may be an electromagnetically actuated relay in which coil 304 is electromagnetic and energising the coil 304 draws a contact of each of the two pole normally open contacts 306, 308 towards the other respective contact thereby closing the contacts 306, 308 and forming conducting circuits thereof.

[0049] Any appropriate relay may be used in place of relay 302.

[0050] The power circuit 302 also includes an electric switch 310. The electric switch 310 consists of switch components ($M_p - 312$ and $M_n - 314$), fast diodes ($D_p - 316$ and $D_n - 318$), resistors ($R_p - 320$, $R_n - 322$ and $R_s - 324$), and a capacitor ($C_s - 326$).

[0051] The switch component 312, presently embodied by a transistor, and the fast diode 318 form a conducting circuit when:

the high frequency AC voltage is positive; and

the driving voltage V_{Gp} between the gate pole (G_p) and the source pole (S_p) of transistor M_p (312) reaches a voltage specified for activating that transistor 312 – i.e. is HIGH.

[0052] In the same way, the switch component 314, also presently embodied by a transistor, and the fast diode 316 form a conducting circuit when:

the high frequency AC voltage is negative; and

the driving voltage V_{Gn} between the gate pole (G_n) and the source pole (S_n) of transistor M_n (314) reaches a voltage specified for activating that transistor 314 – i.e. is HIGH.

[0053] Conversely, the transistors are turned off if the driving voltage between the relevant gates is LOW – e.g. 0 V.

[0054] Using the transistors 312, 314 the electric switch is capable of connecting and disconnecting high frequency AC current. More particularly, the transistors 312, 314 can operate using a small voltages applied to the gates, and those small voltages can be rapidly changed. Thus transistors 312, 314 can use a rapidly changing small voltage to control a much larger current passing from source to sink.

[0055] The high frequency current transducer (HFCT) 328 has a DC voltage input (VCC), a ground input (GND) and an output (V_M). The detected load current is isolated with VCC, GND and M. This may be achieved using any one of a number of sensors. For example, a Hall Effect sensor may sense the current without physically connecting to the live wire or return wire. The voltage of the output (V_M) is proportional to the change in the high frequency current.

[0056] The high frequency leakage current transducer (HFLCT) 330 in FIG. 3a has a positive supply voltage (+V), a negative supply voltage (-V), a ground (GND) and an output (V_{HFLCT}). The energized wire and the returned wire are isolated with +V, -V, GND, and V_{HFLCT} . The output (V_{HFLCT}) is proportional to the difference between the energized high frequency current and the returned high frequency current.

[0057] In the circuit of FIG. 3b, the HFLCT is replaced with the DC leakage current transducer (DCLCT) 332. The transducer 332 comprises an AC-DC-AC converter comprising two full bridge rectifiers 334, 336. Rectifier 334 comprises four fast diodes D_{T1} , D_{T2} , D_{T3} and D_{T4} , and rectifier 336 comprises four fast diodes D_{T5} , D_{T6} , D_{T7} and D_{T8} .

[0058] When the high frequency AC voltage is positive, current passes through diodes D_{T3} , D_{T4} , D_{T5} and D_{T6} , completing the circuit through HFLCT 332. Similarly, when the high frequency AC voltage is negative, current passes through diodes D_{T1} , D_{T2} , D_{T7} and D_{T8} , completing the circuit through HFLCT 332.

[0059] The DC leakage current transducer (DCLCT) 332 has a positive supply voltage (+V), a negative supply voltage (-V), a ground (GND) and an output (V_{DCLCT}). The energized wire and the returned wire are isolated with +V, -V, GND, and V_{DCLCT} . The output (V_{DCLCT}) is proportional to the difference between the energized DC current, indicating the energized high frequency current, and the returned DC current, indicating the returned high frequency current.

[0060] The HFLCT 330 and DCLCT 332 each include a DC-DC converter U_1 (334). Converter 334 converts the external supply voltage (VCC) to a positive voltage (+V) and a negative voltage (-V) to match the positive and negative supply voltages of HFLCT 330 or DCLCT 332. Adjusting the inputs to the converters 334 enables the HFLCT 330 and DCLCT 332 to be calibrated to sense voltages of a desired magnitude.

[0061] In the HFLCT, U_2 (337) is a high-speed operational amplifier (OpAmp) used to filter and amplify output V_{HFLCT} . Similarly in the DCLCT, U_2 (338) is a high-speed operational amplifier (OpAmp) used to filter and amplify output V_{DCLCT} . The relationship between the output (V_{RCDct}) of OpAmp 337 and V_{HFLCT} is expressed as:

$$V_{RCDct} = \left(1 + \frac{R_1}{R_2 + R_3}\right) V_{HFLCT} \quad (\text{Equation 1})$$

and the relationship between the output (V_{RCDct}) of OpAmp 338 and V_{DCLCT} is expressed as:

$$V_{RCDct} = \left(1 + \frac{R_1}{R_2 + R_3}\right) V_{DCLCT} \quad (\text{Equation 2}).$$

[0062] In each case, R_1 , R_2 and R_3 is a resistor group providing negative feedback from the output of the OpAmp 337, 338 back to the negative input terminal. R_3 is a variable impedance (i.e. adjustable regulator) for calibrating the gain of the OpAmp 337, 338. This enables the OpAmp 337, 338 to be calibrated to apply appropriate gain to leakage currents of various sizes. For example, in a first circuit a leakage current of 5mA may be the maximum tolerable leakage before power should be disconnected from the load. In a second circuit a leakage current of 30mA may be the maximum. R_3 enables the same HFLCT 330 or DCLCT 332 to be used in both circuits, with the gain of the OpAmp 337, 338 adjusted so that the first circuit and the second circuit will output the same voltage when their respective thresholds are reached.

[0063] FIG. 3c depicts a typical waveform response with the voltage V_{RAB} across relay 304 controlling the connection of power source 340 to load 342 in FIGs. 3a and 3b. The power source 340 provides an alternating voltage V_{ac} . V_{ac} has no effect until V_{RAB} is high at point 344, at which time gate voltages V_{Gp} and V_{Gn} of transistors 312, 314 alternate HIGH and

LOW states. Thus transistors 312, 314 are activated in alternating fashion. The power passes to the load 342 resulting in voltage V_{Load} and current I_{Load} across the load 342.

[0064] FIG. 4 is a schematic diagram of a high frequency residual-current circuit breaker with overcurrent protection (HFRCCBO) 400, illustrating the various signals passing between the control circuit 402 and the power and sensing circuits 404 and external inputs and outputs. VCC and GND provide the external DC supply (such as 12 V DC supply) powering both the sensing circuit 404 and the control circuit 402. AC_IN1 and AC_IN2 are connected to the high frequency AC supply. AC_OUT1 and AC_OUT2 are connected to the load. These inputs and outputs are further defined with reference to FIGs. 5, 6a, 7a and 8a.

[0065] For illustration purposes the control circuit 500 is divided into three sub-circuits – control circuits A (502), B (504) and C (506) as schematically shown in FIG. 5. Control circuit A (502), shown in detail in FIG. 6a, provides the control signal (V_{Ocb}) for controlling overcurrent protection. Control circuit B (504), shown in detail in FIG. 7a, provides the control signal (V_{RCDb}) for controlling leakage current protection. Control circuit C (506), shown in detail in FIG. 8a, implements the startup or initiation cycle of the HFRCCBO (switch ON – S_{ON}) and the stop cycle of the HFRCCBO (switch OFF – S_{OFF}). Control circuit C (506) also generates the synchronous signals for the electric switch, the driving voltages to two switch components (e.g. G_p-S_p and G_n-S_n for transistors 312, 314), and the driving voltage to the control coil 304 of the relay 302 (R_A-R_B).

[0066] With further reference to FIG. 5:

V_{RCDct} is the leakage current signal from the sensing circuit is an input to Control circuit B (504);

T_1 and T_2 are connected to the power circuit for testing the leakage current protection, and are inputs to Control circuit B (504);

V_M is the load current signal from the sensing circuit is an input to Control circuit A (502);

VCC and GND are the external DC supply (such as 12 V DC supply) powering the sensing circuit and the control circuit;

AC_IN1 and AC_IN2 are connected to the high frequency AC supply and acquire the synchronous signals for the high frequency AC voltage and are inputs to Control circuit C (506);

R_4 and R_7 are the contacts of the relay 302 in the power circuit and are outputs of Control circuit C (506);

R_A and R_B are connected to the control coil of the relay in the power circuit and are outputs of Control circuit C (506);

G_p-S_p and G_n-S_n control the driving gate voltages for switch components 312, 214, presently two metal-oxide-semiconductor-field-effect-transistors (MOSFETs – M_p and M_n) in the power circuit, respectively.

[0067] FIG. 6a illustrates an exemplary embodiment of Control circuit A (502) that provides the control signal V_{OCb} for controlling overcurrent protection. The circuit 502 is, as discussed above, used in a high frequency circuit breaker (HFCB), the HFCB comprising a sensing circuit for sensing a current passing through a load, and a power circuit for connecting and disconnecting power to the load. In the embodiment shown in FIG. 6a, the control circuit (or sub-circuit as the case may be) comprises an analog comparator 606, comprising OpAmp U₃ (600) and an switched state retention circuit 608.

[0068] Analog comparator 606 compares an output from the sensing circuit (V_M) to a current reference (V_{OCref}). And switched state retention circuit 608 provides a control signal to the power circuit (see 224 of FIG. 2a and 224' of FIG. 2b) based on an output from the analog comparator, to force the power circuit to selectively connect or disconnect power to the load. Using these circuits 606 and 608, control circuit 502 provides a control signal for monitoring load current and controlling disconnection of power to a load in an overcurrent event.

[0069] The component U₃ (600) is a comparator that detects overcurrent. Component 600 may be a high-speed comparator integrated circuit (IC). As shown, component 600 is an OpAmp. OpAmp 600 is powered by VCC and VCC also contributes to a positive feedback loop 602 of component 600. Thus the OpAmp 600 and the current reference are driven by a common direct current (DC) input voltage VCC.

[0070] The positive feedback loop provides the current reference. The current reference comprises a variable impedance ($R_6 - 604$). It also presently comprises an impedance (R_8). Changing an impedance of the variable impedance 604 adjusts the current reference.

[0071] The current reference is applied at the positive terminal of the OpAmp 600 and the sensed load current is applied at the negative terminal of the OpAmp 600. Thus if the current reference is greater than the sensed load current, the output of OpAmp 600 will be HIGH and the circuit 502 will operate normally. If the current reference is at least as large as the sensed load current, the output of OpAmp 600 will be LOW and trigger overcurrent protection.

[0072] The output of comparator circuit 606 is delivered to the switched state retention circuit 608. If the output of the comparator circuit 606 is HIGH the switched state retention circuit 608 shown in FIG. 6a will maintain a HIGH output (V_{OCb}). If the output of the comparator circuit 606 is LOW the switched state retention circuit 608 shown in FIG. 6a will switch to a LOW output (V_{OCb}).

[0073] With reference to the embodiments shown in FIGs. 2a and 2b, the circuit 502 comprises comparator 208. Thus the output (V_{OCb}) is sent from comparator 208 to AND gate 220. Accordingly, a HIGH output from comparator 208 will cause the state of the AND gate to rely on its other input(s). Conversely, a LOW output from comparator 208 will pull the AND gate output LOW. That LOW output will result in the power circuit 224, 224' disconnecting power to the load 232.

[0074] Desirably, the switched state retention circuit 608 should maintain a LOW output upon experiencing an overcurrent event, to ensure the circuit does not recommence normal operation until the overcurrent event is rectified. To facilitate state retention – e.g. maintaining a LOW output on experiencing an overcurrent event – the switched state retention circuit 608 comprises a not-OR (NOR) circuit. The NOR circuit comprises multiple NOR gates.

[0075] The NOR functionality is implemented by components U_4 (610) and U_5 (612). These components 610, 612 may be the complementary metal-oxide-semiconductor (CMOS) NOR gate ICs

[0076] Since the circuit 502 is used in a high frequency environment, the circuit 502 has a very short time in which to switch the NOR gates in an overcurrent event. A sinusoidal analog input is only at its peak (or trough) for a brief period, yet it can be desirable to have a slightly longer period to ensure changes in state of the outputs of the NOR gates can propagate through the circuit 502 before the inputs to the circuit 502 change. In other words, to ensure proper NOR gate switching.

[0077] To provide a NOR gate input that is sufficiently sustained to facilitate switching and output propagation, the switched state retention circuit 608 includes an hysteresis block or component U_6 (614). The hysteresis component 614 has a non-linear relationship between its input and output to maintain an output in spite of minor changes in its input. This also helps eliminate noise from its input. For example, if the component 614 output is LOW, it will only change to HIGH once the input exceeds a positive (i.e. HIGH) threshold value. The component 614 output will only then revert to LOW once the input exceeds – i.e. drops below – a negative (i.e. LOW) threshold value. This can result in an AC sinusoidal input producing a square wave output through component 614. Advantageously, maintaining a value for longer, as achieved using a square wave, gives a NOR gate sufficient time to change its output and to have the effects of that output propagate in the circuit 502 before the input changes. Thus the effect of an overcurrent can propagate through the switched state retention circuit 608 before the input V_M reduces and no longer indicates an overcurrent. This enables the overcurrent event to be captured even when it is not indicated on the input for very long.

[0078] In the present embodiment, component 614 consists of inverting Schmitt-trigger circuits. There are six in the present component 614 as this is a standard component, though only three triggers are used. The triggers function as inverters with Schmitt-trigger action on the inputs.

[0079] Hysteresis component 614 is used to control the indicator Lamp₁ (616) and to clean up the input – e.g. remove noise – to make it more reliable when controlling switching of the NOR gates as discussed above. When there is no overcurrent, Lamp₁ 616 does not light. Conversely, when an overcurrent occurs the Lamp₁ 616 illuminates.

[0080] The output voltage of comparator 602 (V_{OC}) is HIGH if the output voltage (V_{CT}) of the HFCT (see, e.g., reference 328 in FIGs. 3a and 3b) is less than the overcurrent reference (V_{OCref}). The output of the switched state retention circuit 608 (V_{OCb}) is HIGH due to the HIGH level of V_{OC} . Consequently, the indicator Lamp₁ does not light. In other words, the output from the analog comparator 606 can have multiple states. Presently there are two states including a first state (HIGH) indicating the output from the sensing circuit (HFCT) does not exceed the current reference (V_{OCref}), and a second state (LOW) indicating the output from the sensing circuit (HFCT) exceeds the current reference (V_{OCref}). Similarly, the control signal from the switched state retention circuit 608 can have multiple states. Presently there are two states including a first control state (HIGH) for forcing the power circuit to connect (which includes maintain connection of) power to the load and a second control state (LOW) for forcing the power circuit to disconnect power to the load. Moreover, the control signal sent from the switched state retention circuit 608 switches from the first control state (HIGH) to the second control state (LOW) once the output from the analog comparator switches from the first state (HIGH) to the second state (LOW).

[0081] Conversely, V_{OC} is LOW if the output voltage (V_{CT}) of the HFCT is more than the overcurrent reference (V_{OCref}). The output of the component 606 (V_{OCb}) is similarly LOW due to the LOW level of V_{OC} . Consequently, the indicator Lamp₁ lights. After this, V_{OCb} keeps the LOW level and the Lamp₁ remains illuminated until the reset switch Reset₁ (622) is trigger – e.g. pushed, in the case of a reset button.

[0082] In effect, the switched state retention circuit 608 has two states. As discussed above, switching of the switched state retention circuit 608 to the second, LOW state, depends on the input from the analog comparator 602. However, when the control signal attains the second, LOW state it maintains that state regardless of changes in the output from the analog comparator 608. In order for the high frequency circuit breaker to function again, the output of the circuit 502 (i.e. the output from the switched state retention circuit 608 (V_{OCb})) must be driven HIGH. Activation of reset switch 622 achieves this by changing an input to one of the NOR gates as discussed with reference to FIG. 6a, forcing the switched state retention circuit 602 to the first, HIGH state provided the output of the analog comparator 602 is in the first, HIGH state. Notably, if the output of the analog comparator 602 is LOW, then activation of the reset switch 622 will have no effect on the output V_{OCb} .

[0083] When the output V_{OCb} of the switched state retention circuit 608 is in the second, LOW state, that state is maintained by two particular NOR gates 618, 620. Each of the two NOR gates 618, 620 provides an input to the other NOR gate 618, 620. In particular, gate 618 takes a first input from gate 620 and a second input that is effected by the output of the analog comparator 602 – e.g. the output V_{OC} is inverted such that when V_{OC} is HIGH, the second input to gate 618 is LOW and vice versa. This effect is particularly evident when the comparator 602 switches from its first, HIGH state to its second, LOW state – i.e. indicates an overcurrent. Similarly, gate 620 takes a first input from gate 618, and its second input is affected by activation of the reset switch 622.

[0084] The typical waveforms of the control circuit 502 are shown in FIG. 6b. At 624 the output from the HFCT V_{CT} steps up to exceed the load current reference V_{OCref} , indicating an overcurrent. This drives LOW the output V_{OCb} sent from gate 618 and thus from switched state retention circuit 608. With reference to FIG. 2a, the LOW output drives the AND gate 220 LOW, the LOW output of the AND gate 220 then being amplified by amplifier 222 before forcing the power circuit 224 to disconnect power from the load 232. At 626 the overcurrent event ceases but V_{OCb} remains LOW until the reset is activated at 628. Another overcurrent event occurs at 630. Reset is activated at 632 but has no effect on output V_{OCb} since the overcurrent event still persists until 634. Another reset activation occurs at 636 and is successful since the overcurrent event has ceased.

[0085] FIG. 7a illustrates an exemplary embodiment of Control circuit B (504) that provides the control signal V_{RCDb} for controlling overcurrent protection. The circuit 504 is, as discussed above, used in a high frequency circuit breaker (HFCB), the HFCB comprising a sensing circuit for sensing a current passing through a load, and a power circuit for connecting and disconnecting power to the load. Circuits 502 and 504 may both be supplied in a common HFCB, or only one may be supplied. In the embodiment shown in FIG. 7a, the control circuit (or sub-circuit as the case may be) comprises an analog comparator 706, comprising OpAmp U_7 (700) and an switched state retention circuit 708.

[0086] Analog comparator 706 compares an output from the sensing circuit (V_{RCDet}) to a current reference (V_{RCDref}). And switched state retention circuit 708 provides a control signal

to the power circuit (see 224 of FIG. 2a and 224' of FIG. 2b) based on an output from the analog comparator 706, to force the power circuit to selectively connect or disconnect power to the load. Using these circuits 706 and 708, control circuit 504 provides a control signal for monitoring leakage current and controlling disconnection of power to a load when leakage current exceeds a predetermined threshold specified by the feedback loop 702 of comparator 706.

[0087] The component U_3 (700) is a comparator that detects leakage current. Component 700 may be the high-speed comparator integrated circuit (IC). As shown, component 700 is an OpAmp. OpAmp 700 is powered by VCC and VCC also contributes to a positive feedback loop 702 of component 700.

[0088] The positive feedback loop provides the leakage current reference. The leakage current reference comprises a variable impedance (R_{16} – 704) and an impedance (R_{18}). Changing an impedance of the variable impedance 704 adjusts the leakage current reference.

[0089] The leakage current reference is applied at the positive terminal of the OpAmp 700 and the sensed leakage current is applied at the negative terminal of the OpAmp 700. Thus if the leakage current reference is greater than the sensed leakage current, the output of OpAmp 700 will be HIGH and the circuit 504 will operate normally. If the leakage current reference is at least as large as the sensed leakage current, the output of OpAmp 700 will be LOW and trigger leakage current protection.

[0090] The output of comparator circuit 706 is delivered to the switched state retention circuit 708. If the output of the comparator circuit 706 is HIGH the switched state retention circuit 708 shown in FIG. 7a will maintain a HIGH output (V_{RCDb}). If the output of the comparator circuit 706 is LOW the switched state retention circuit 708 shown in FIG. 7a will switch to a LOW output (V_{RCDb}).

[0091] With reference to the embodiments shown in FIGs. 2a and 2b, the circuit 504 comprises comparator 206. Thus the output (V_{RCDb}) is sent from comparator 206 to AND gate 220. Accordingly, a HIGH output from comparator 206 will cause the state of the AND gate to rely on its other input(s). Conversely, a LOW output from comparator 206 will pull

the AND gate output LOW. That LOW output will result in the power circuit 224, 224' disconnecting power to the load 232.

[0092] Desirably, the switched state retention circuit 708 should maintain a LOW output upon experiencing a leakage current event, to ensure the circuit does not recommence normal operation until the leakage current event is resolved. To facilitate state retention – e.g. maintaining a LOW output on experiencing a leakage current event – the switched state retention circuit 708 comprises a not-OR (NOR) circuit similar to that of circuit 502. The NOR functionality is implemented by components U_8 (710) and U_9 (712). These components 710, 712 may be complementary metal-oxide-semiconductor (CMOS) NOR gate ICs.

[0093] To provide a NOR gate input that is sufficiently sustained to facilitate switching, the switched state retention circuit 708 includes a hysteresis block or component U_{10} (614). The hysteresis component 714 has the same properties and operates with the same functionality in respect of leakage current as that described in respect of hysteresis component 614 for overcurrent.

[0094] Hysteresis component 714 is used to control the indicator Lamp₂ (716). When there is no overcurrent, Lamp₂ 716 does not light. Conversely, when an overcurrent occurs the Lamp₂ 716 illuminates.

[0095] The output voltage of comparator 702 (V_{RCD}) is HIGH if the output voltage (V_{RCDct}) of the HFLCT (see, e.g., reference 330 in FIG. 3a) or the DCLCT (see, e.g., reference 332 in FIG. 3b) is less than the leakage current reference (V_{RCDref}). The output of the component 708 (V_{RCDb}) is HIGH due to the HIGH level of V_{RCD} . Consequently, the indicator Lamp₂ does not light. In other words, the output from the analog comparator 706 and the switched state retention circuit 708 can have multiple states, presently two states each, that are effected in the same manner by the HFLCT and reset switch 722 as described above in respect of the HFCT and reset switch 622 affecting the outputs of comparator 606 and switched state retention circuit 608.

[0096] When the output V_{RCDb} of the switched state retention circuit 708 is in the second, LOW state, that state is maintained by two particular NOR gates 718, 720. The operation of the NOR gates 718, 720 is the same as that of NOR gates 618, 620.

[0097] The typical waveforms of the control circuit 504 are shown in FIG. 7b. At 724 the output from the HFLCT V_{RCDct} steps up to exceed the load current reference V_{RCDref} , indicating an unacceptably high leakage current. This drives LOW the output V_{RCDb} sent from gate 718 which is also the output from switched state retention circuit 708. With reference to FIG. 2a, the LOW output drives the AND gate 220 LOW, the LOW output of the AND gate 620 then being amplified by amplifier 222 before forcing the power circuit 224 to disconnect power from the load 232. At 726 the leakage current event ceases but V_{RCDb} remains LOW until the reset is activated at 728. Another leakage current event occurs at 730. Reset is activated at 732 but has no effect on output V_{RCDb} since the leakage current event still persists until 734. Another reset activation occurs at 736 and is successful since the leakage current event has ceased.

[0098] A test circuit 738 is also shown in FIG. 7a. Circuit 738 is used to examine the effectiveness of the leakage current protection provided by circuit 504. A leakage current with specified value occurs on activation of button S_t , resulting in current leakage between terminals T_1 and T_2 , across resistor R_{14} . Terminals T_1 , T_2 of the test circuit are connected across the active (live) and return terminals of the HFLCT or DCLCT – see, e.g., HFLCT 330 in FIG. 3a and DCLCT 332 in FIG. 3b. In a successful test, the current leakage across circuit 738 pulls V_{RCDct} LOW and results in indicator lamp $Lamp_2$ illuminating.

[0099] Control circuit 506, illustrated in FIG. 8a, can provide the AND-gate functionality (see reference 220 in FIGs. 2a and 2b) and the amplification functionality (see reference 222 in FIGs. 2a and 2b). Notably, circuit 506 can be readily modified to exclude one of those functions if the design of the HFCB permits it.

[00100] Control circuit 506 implements the start of the HFRCCBO (S_{ON}) – i.e. provides the startup or initiation inputs – and the stop of the HFRCCBO (S_{OFF}). Circuit 506 may generate synchronous signals for the electric switch (V_{P1} and V_{N1}). Circuit 506 may also, or alternatively, generate the driving voltages (G_p-S_p and G_n-S_n) to two switch components 312,

314. The circuit 506 may further, or alternatively, generate the driving voltage (R_A-R_B) to the control coil 304 of the relay 302.

[00101] V_{P1} is the synchronous signal to the positive high frequency supply voltage applied to terminal AC_IN1 (800) and V_{N1} is the synchronous signal to the negative high frequency supply voltage applied to terminal AC_IN2 (802), where terminals AC_IN1 and AC_IN2 are connected to the high frequency AC supply – see, e.g., reference 340 of FIG. 3a.

[00102] Components U_{11} (804), U_{12} (806), U_{14} (808) and U_{15} (810) are used to isolate the inputs with the outputs and may be high-speed optocouplers. Component U_{13} (812) is to provide an AND function. Component 812 may a CMOS AND-gate IC.

[00103] Components U_{16} (814) and U_{17} (816) produce the driving voltages used by the power circuit to connect (including maintaining connection) and disconnect power to the load. Component 814 supplies driving voltage(s) to the switch component(s) of the power circuit, and component 816 supplies the driving voltage(s) to the relay component(s) – i.e. control coil – of the power circuit. Components 814, 816 are thus high-speed drivers for applications that require low current digital signals to drive large capacitive loads, such as power switch components mentioned above. To enable low current signals to drive large loads, OpAmps are used. Component 814 may comprise a pair of OpAmps, one for each control signal. Similarly, component 816 comprises an OpAmp for amplifying the control signal to the control coil of the relay, and an external power supply (VCC, GND).

[00104] Component 814 is used to amplify two control signals. The control signals are used as driving voltages outputted to the two switch components 312, 314 shown in FIGs. 3a and 3b. The number of signals amplified by component 814 will depend on the number of switch components used in the HFCB. Similarly, in some embodiments a single output can be used to drive multiple switch components. However, in the present case the switch components operate 180° out of phase and thus require separate signal sources.

[00105] Circuit 506 comprises a voltage matching device, component U_{18} (818), for converting an external supply voltage V_{CC} to an isolated voltage used for matching the supply voltage of component 814. Presently, component 818 is a DC-DC converter.

[00106] Circuit 506 also includes a start button (S_{ON}) 822 activation of which drives input voltages, and other inputs as necessary, to the HFCB to desired levels to commence proper functioning of the HFCB. Without overcurrent protection and leakage current protection activated, the output V_{OCb} of circuit 502 and V_{RCDb} of circuit 504 are HIGH. The indicator Lamp₃ 820 lights. The driving voltage V_{RAB} is supplied across terminals R_A , R_B (824) to activate the control coil of the relay (R_A - R_B) once the start button 822 is pushed. Consequently, the contacts (R_7 - R_4 and R_9 - R_6) of the relay are closed. This bypass switch 822 and maintains operation of relay.

[00107] Meanwhile, component 814 outputs a driving voltage to the switch (e.g. reference 310 of FIGs. 3a and 3b). The switch component (e.g. transistor 312, 314) activated by the driving voltage will depend on when, during the AC cycle, the button 822 is pressed.

[00108] A stop button 826 (S_{OFF}) is also provided, to cease operation of the HFCB. On activation of button 826, power to the driving voltage V_{CC} disconnects. The indicator (Lamp₃) thus switches off and the driving voltage supplied to the control coil of the relay (V_{RAB}) goes to zero. Consequently, the contacts (R_7 - R_4 and R_9 - R_6) open.

[00109] Meanwhile, the driving voltage to M_p (V_{Gp}) and the driving voltage to M_n (V_{Gn}) go to zero. Thus, with reference to FIG. 3a, the relay 302 and switch 310 both open, thereby disconnecting power to the load 342.

[00110] Similarly, if either one of V_{OCb} and V_{RCDb} is LOW, this drives outputs of components 812, 808 LOW, thereby switching off Lamp₃ 820. The driving voltages (V_{RAB}) to the relay and switch also become LOW.

[00111] Typical waveforms of the control circuit 506 are illustrated in Fig. 8b. Before 828 the power source voltage V_{ac} is sinusoidal, and the terminal supply voltages V_{P1} and V_{N1}

provide opposing square waveforms. Also, V_{OCb} and V_{RCDb} are HIGH, indicating there is no overcurrent or unacceptable leakage current condition. Activation of switch 822 at point 828 connects power to the load. This draws to HIGH level the voltage across the relay, V_{RAB} , and the voltage across the lamp, V_{Lamp3} . Also, the gate voltages for transistors 312, 314 of the switch are powered using opposing square waveforms (see reference 830). At 832 the stop button 826 is activated, cutting power to the load by drawing the relay and gate voltages V_{RAB} , V_{Gp} and V_{Gn} LOW. Power to the load is reconnected at 834 by pressing the start button 822, and at 836 the HFCB trips as a result of one or both of the HFCT and HFLCT or DCLCT outputs going LOW and thereby indicating an overcurrent event and/or leakage current event.

[00112] A control circuit formed using the sub-circuits 502, 504 and 506 of FIGs. 6a, 7a and 8a respectively, and thus the overall operation of the HFRCCBO is as follows: if the sensed current signal (V_{CT}) sent from the HFCT is less than the current reference (V_{OCref}), the actual load current is less than the specified load current. Consequently, the output of component 610 (V_{OCb}) is HIGH and Lamp₁ does not light. Thus, overcurrent protection is not activated.

[00113] If the sensed current signal (V_{CT}) is not less than the current reference signal (V_{OCref}), the actual load current is not less than the specified load current. Consequently, the output of the component 610 (V_{OCb}) is LOW and the indicator (Lamp₁) lights. This activates overcurrent protection by drawing the AND-gate LOW, resulting in low power to the power circuit and thus disconnecting power from the load.

[00114] Similarly, if the sensed leakage current signal (V_{RCDct}) is less than the leakage current reference signal (V_{RCDref}), the actual leakage current is less than the specified leakage current. The output of component 710 (V_{RCDb}) is HIGH and the indicator (Lamp₂) does not light. Thus leakage current protection is not activated.

[00115] If the actual leakage current is not less than the specified leakage current, the sensed leakage current signal (V_{RCDct}) is not less than the leakage current reference signal (V_{RCDref}). Consequently, the output of component 710 (V_{RCDb}) is LOW and the indicator

Lamp₂ illuminates. This activates leakage current protection by drawing the AND-gate LOW, resulting in low power to the power circuit and thus disconnecting power from the load.

[00116] If the start button 822 is pushed, the indicator (Lamp₃) lights and the driving voltage (V_{RAB}) outputted by component 816 is applied to the control coil (R_A-R_B) of the relay (Re). Consequently, the contacts (R_7-R_4 and R_9-R_6) of the relay (Re) are closed. By closing contacts R_7-R_4 start button 822 is bypassed, and by closing contacts R_9-R_6 points P1 and P1 in the power circuit are connected. The gate voltages V_{Gp} and V_{Gn} are alternately activated, closing the switch of the power circuit and the high frequency AC supply is applied to the load.

[00117] If the stop button 826 is pushed, the indicator 820 does not light and the driving voltage (V_{RAB}) output by component 816 is zero. Consequently, contacts R_7-R_4 and R_9-R_6 of the relay are opened. This disconnects points P1 and P2 in the power circuit. The two driving voltages V_{Gp} and V_{Gn} outputted by the component 814 become zero, switching off transistors 312, 314 and diodes 316, 318. This disconnects points P2 and P3 in the power circuit. Therefore, the high frequency AC supply is disconnected from the load.

[00118] If an overcurrent occurs, the output of component 610 (V_{OCb}) is driven LOW, the indicator lamp 616 illuminates and high frequency AC supply is disconnected from the load as per depression of stop button 826. Furthermore, the V_{OCb} output maintains the LOW level and the indicator Lamp₁ 616 remains illuminated until the Reset₁ 622 is pushed.

[00119] If a leakage current event occurs, the output of component 710 (V_{RCDb}) is driven LOW, the indicator lamp 716 illuminates and high frequency AC supply is disconnected from the load as per depression of stop button 826. Furthermore, the V_{OCb} output maintains the LOW level and the indicator Lamp₁ 616 remains illuminated until the Reset₁ 622 is pushed. Furthermore, the V_{RCDb} output maintains the LOW level and the indicator Lamp₂ 716 remains illuminated until the Reset₂ 722 is pushed.

[00120] It will be understood that many variations and combinations of the above circuits will be apparent to the skilled person upon reading the present disclosure. The present

embodiments are for illustration purposes only and the scope of the disclosure is to be found in the claims.

CLAIMS

1. A control circuit for a high frequency circuit breaker (HFCB), the HFCB comprising a sensing circuit for sensing at least one of a high frequency leakage current and a high frequency current passing through a load, and a power circuit for connecting and disconnecting power to the load, the control circuit comprising:
 - an analog comparator for comparing an output from the sensing circuit to a current reference; and
 - a switched state retention circuit for providing a control signal to the power circuit based on an output from the analog comparator, to force the power circuit to selectively connect or disconnect power to the load.
2. A control circuit according to claim 1, wherein output of the analog comparator is based on a difference between the output from the sensing circuit and the current reference.
3. A control circuit according to claim 1 or 2, wherein the output from the sensing circuit comprises a voltage, the current reference comprises a voltage indicative of a threshold current, and the analog comparator identifies a voltage differential.
4. A control circuit according to any preceding claim, wherein the analog comparator comprises a high speed comparator integrated circuit (IC).
5. A control circuit according to any preceding claim, wherein the analog comparator comprises a differential operational amplifier (OpAmp) for determining a difference between the output from the sensing circuit and the current reference.
6. A control circuit according to claim 4, wherein the OpAmp and the current reference are driven by a common direct current (DC) input voltage.
7. A control circuit according to any preceding claim, wherein the current reference comprises a variable impedance and an impedance, and changing an impedance of the variable impedance adjusts the current reference.

8. A control circuit according to any preceding claim, wherein the output from the analog comparator has a first state indicating the output from the sensing circuit does not exceed the current reference, and a second state indicating the output from the sensing circuit exceeds the current reference.
9. A control circuit according to claim 8, wherein the control signal from the switched state retention circuit has a first control state for forcing the power circuit to connect power to the load and a second control state for forcing the power circuit to disconnect power to the load.
10. A control circuit according to claim 9, wherein the control signal switches from the first control state to the second control state once the output from the analog comparator switches from the first state to the second state.
11. A control circuit according to claim 8 or 9, wherein when the control signal attains the second state it maintains the second state regardless of changes in the output from the analog comparator.
12. A control circuit according to claim 9 or 10, further comprising a reset switch activation of which forces the switched state retention circuit to the first state if the output of the analog comparator is in the first state.
13. A control circuit according to any preceding claim, wherein the switched state retention circuit comprises a not-OR (NOR) circuit comprising multiple NOR gates and an inverter circuit comprising multiple inverters.
14. A control circuit according to any preceding claim, wherein the control circuit is for receiving an output from a sensing circuit comprising:
 - a first high frequency current transducer for sensing a load current and leakage current;
 - and

a second high frequency current transducer for sensing the other of the load current and leakage current; and

the control circuit comprises:

a first sub-circuit comprising:

the comparator, being a first comparator, for comparing an output from the first high frequency current transducer to a respective load current reference or leakage current reference; and

the switched state retention circuit, being a first switched state retention circuit; and

a second sub-circuit comprising:

a second analog comparator for comparing an output from the second high frequency current transducer to a respective load current reference or leakage current reference; and

a second switched state retention circuit for providing a control signal to the power circuit based on an output from the second analog comparator, to force the power circuit to selectively connect or disconnect power to the load.

15. A control circuit according to claim 13 when dependent on claim 12, wherein two of the NOR gates are used to maintain the second state of the switched state retention circuit and: each of the two NOR gates provides an input to the other; an input of the two NOR gates is affected by activation of the reset switch; and an input of the other of the two NOR gates is affected by output of the analog comparator change from the first state to the second state.

16. A high frequency circuit breaker (HFCB) comprising:
a control circuit;
a sensing circuit for sensing at least one of a high frequency leakage current and a high frequency current passing through a load; and
a power circuit for connecting and disconnecting power to the load,
wherein the control circuit comprises:
an analog comparator for comparing an output from the sensing circuit to a current reference; and

a switched state retention circuit for providing a control signal to the power circuit based on an output from the analog comparator, to force the power circuit to selectively connect or disconnect power to the load.

17. A HFCB according to claim 16, wherein the power circuit comprises a relay and a switch each of which is switchable between an ON state and an OFF state.

18. A HFCB according to claim 17, wherein the relay and switch are in series such that if either one of the relay and switch switches to the OFF state, power is disconnected to the load.

19. A HFCB according to claim 17, wherein the relay and switch are in parallel such that power is connected to the load once either one of the relay and switch is switched to the ON state.

20. A HFCB according to any one of claims 16 to 19, wherein the sensing circuit comprises a DC residual-current transducer and two AC-DC rectifiers.

21. A HFCB according to claim 20, wherein the power circuit comprises two outputs, the load comprises two terminals and the AC-DC rectifiers each include an input, wherein:

one output of the power circuit and one terminal of the load provide an AC input to one of the two AC-DC rectifiers; and

the other output of the power circuit and the other terminal of the load provide the other AC input to the other of the two AC-DC rectifiers.

22. A HFCB according to claim 20 or 21, wherein each AC-DC rectifier comprises a DC output and a difference between the DC outputs provides an input of the DC residual-current transducer, and an output of the DC residual-current transducer is isolated with the input of the DC residual-current transducer.

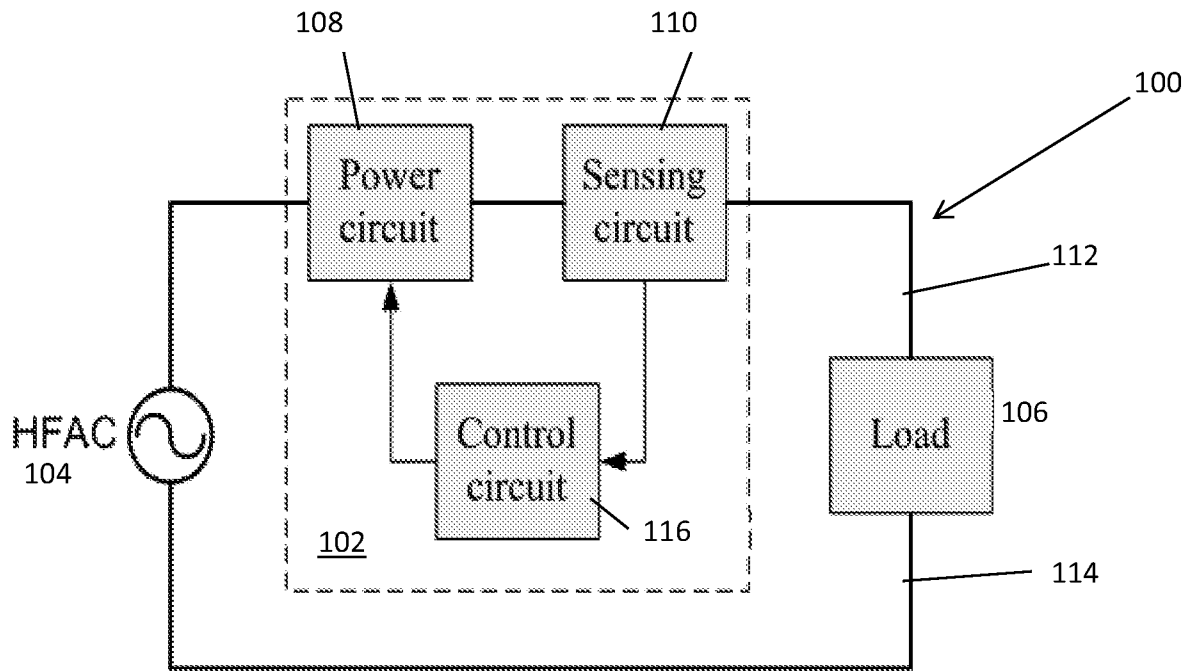


FIG. 1

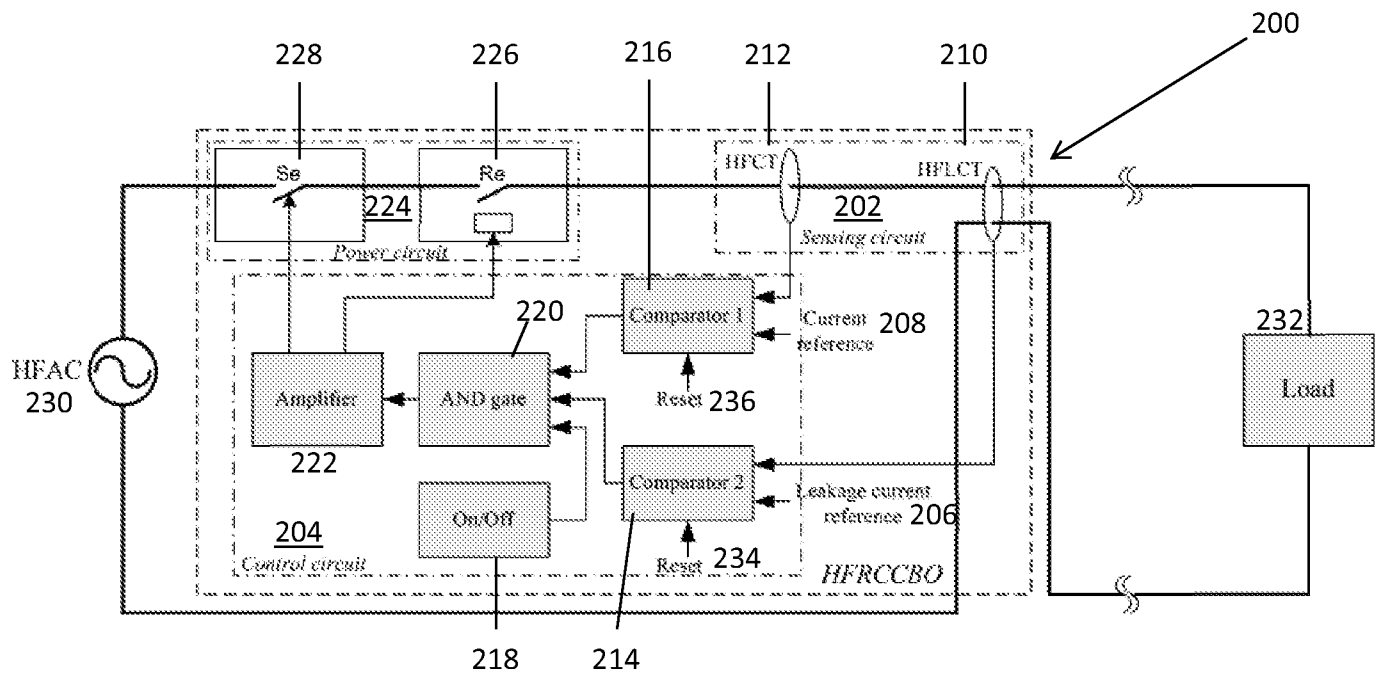


FIG. 2a

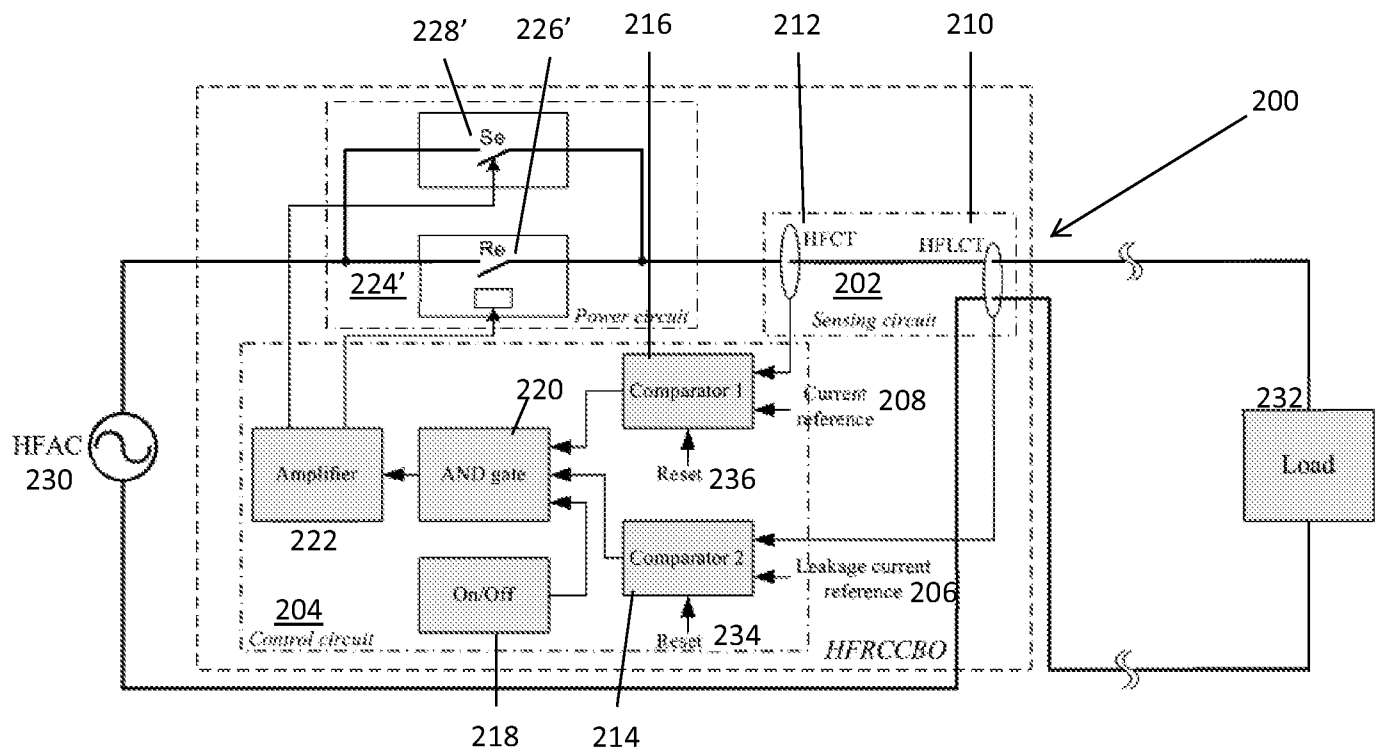


FIG. 2b

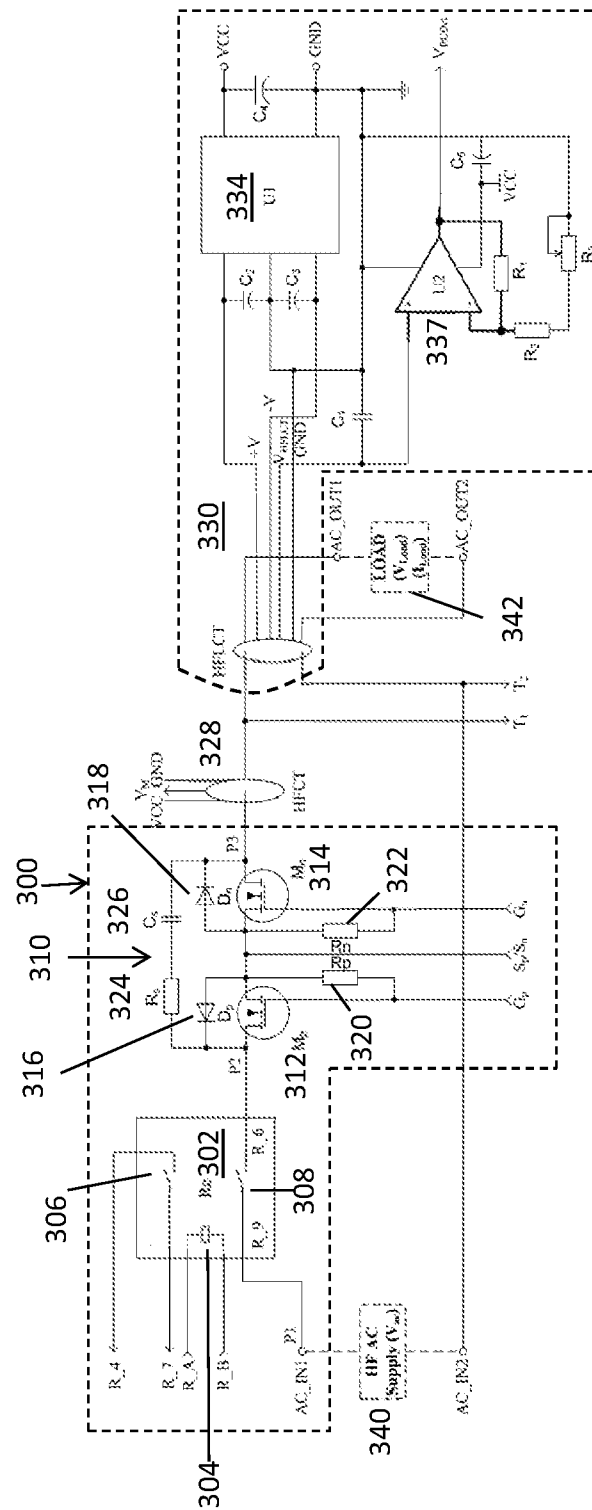


FIG. 3a

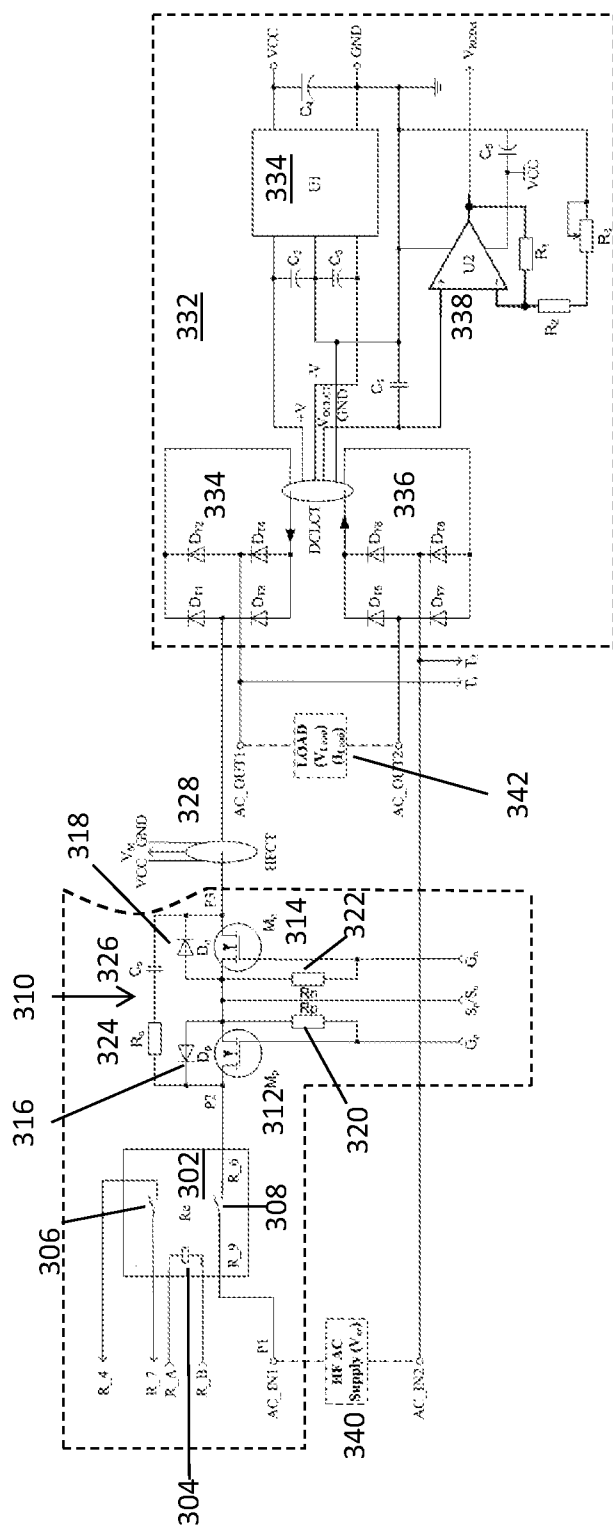


FIG. 3b

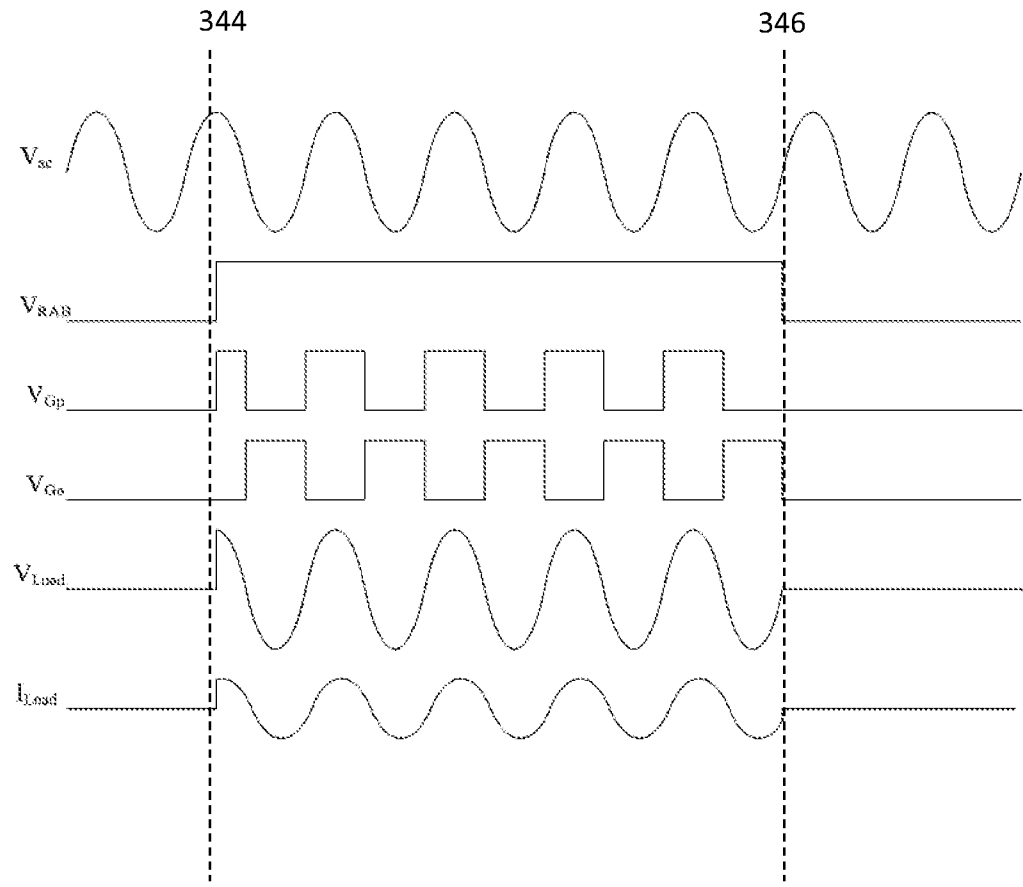


FIG. 3c

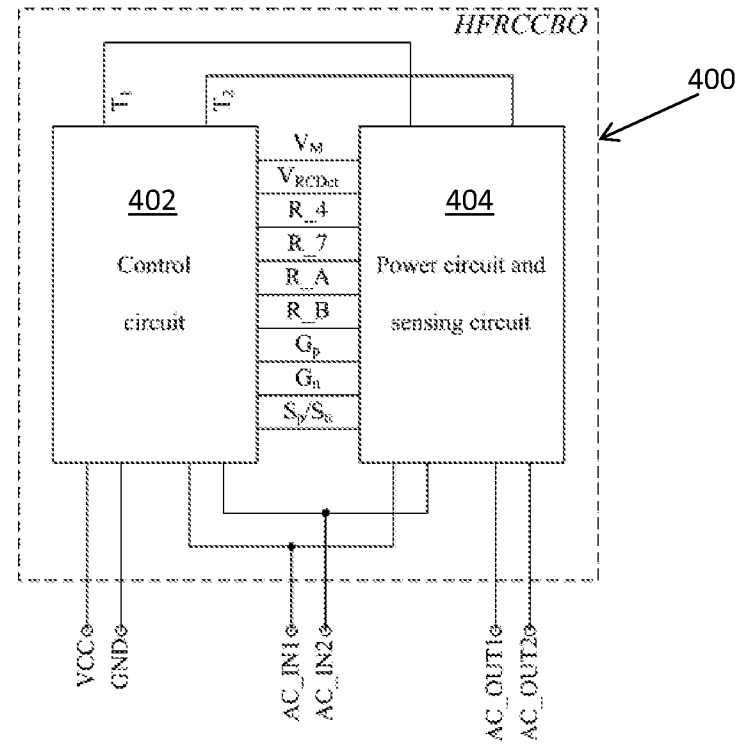


FIG. 4

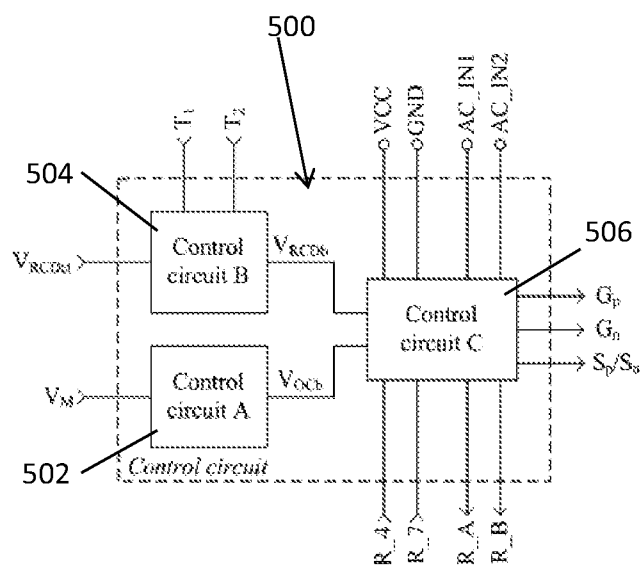


FIG. 5

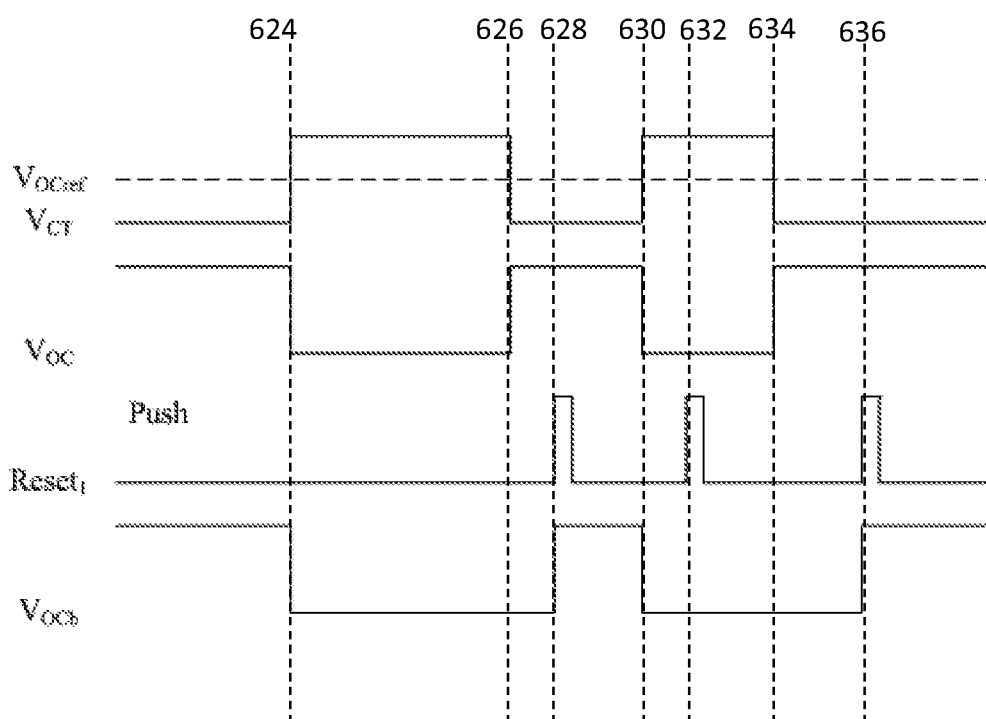


FIG. 6b

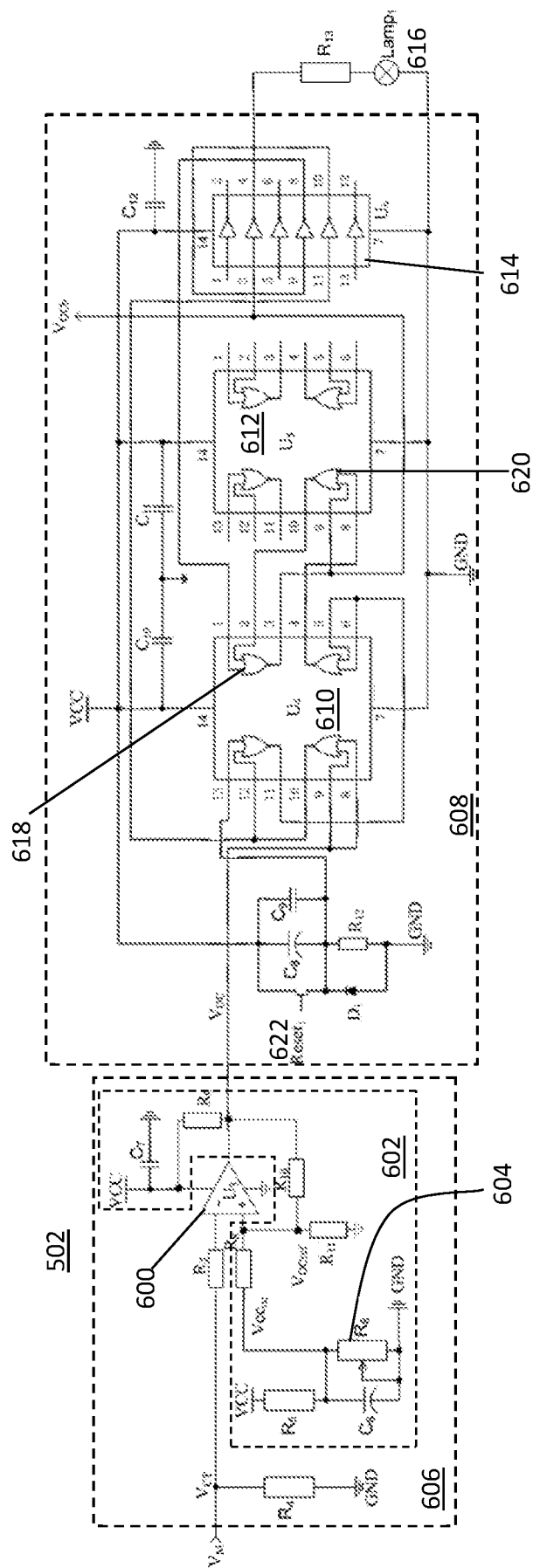


FIG. 6a

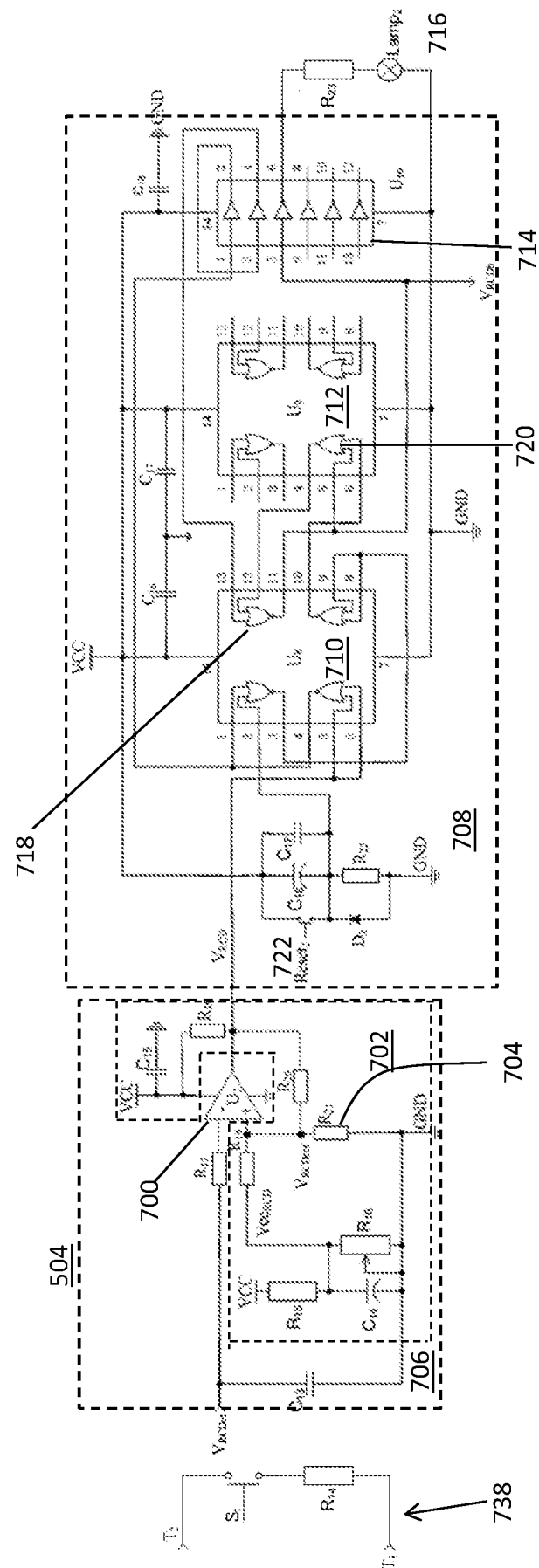


FIG. 7a

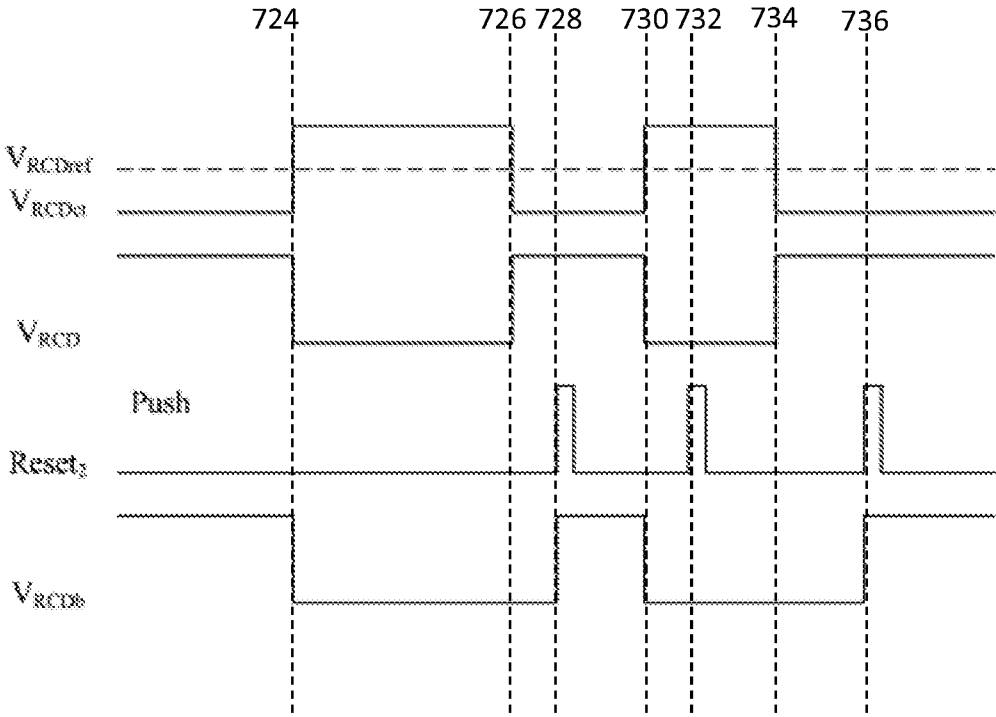


FIG. 7b

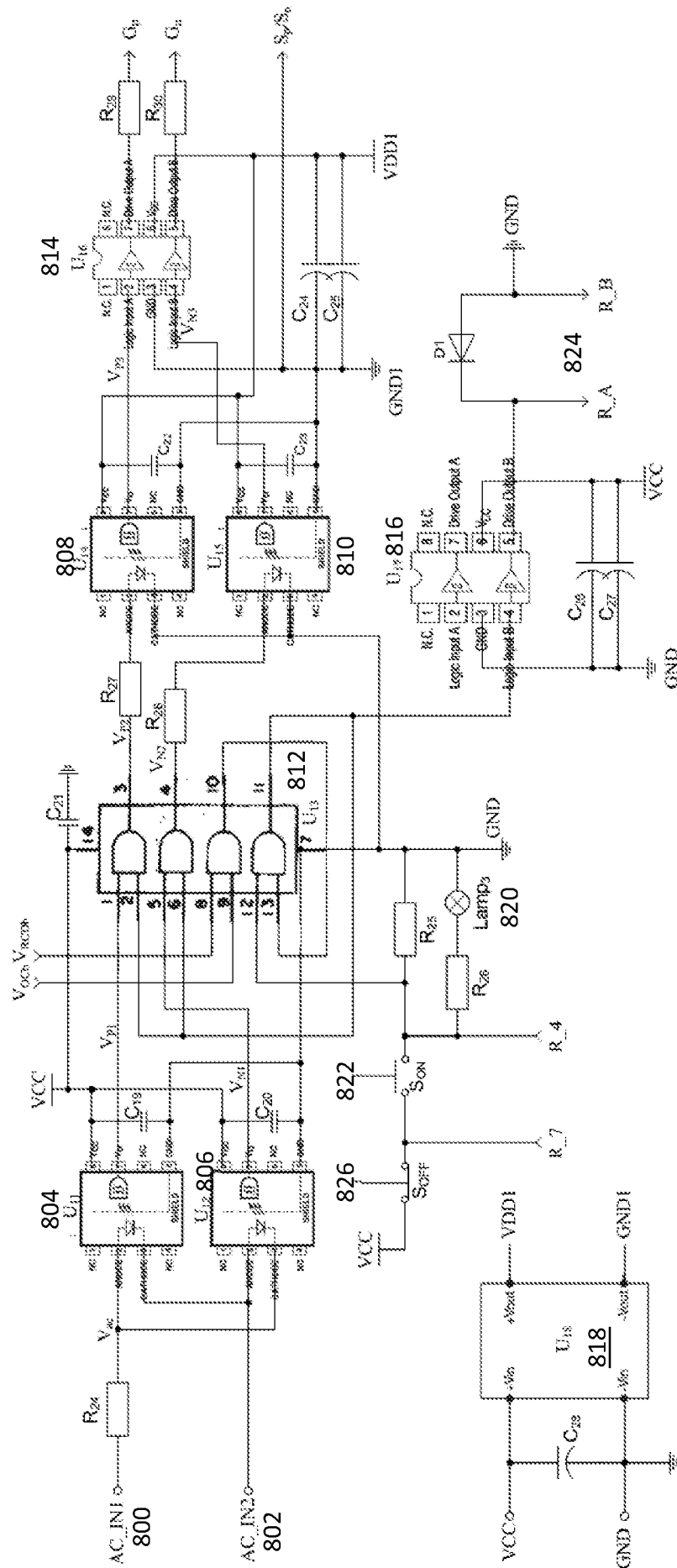


FIG. 8a

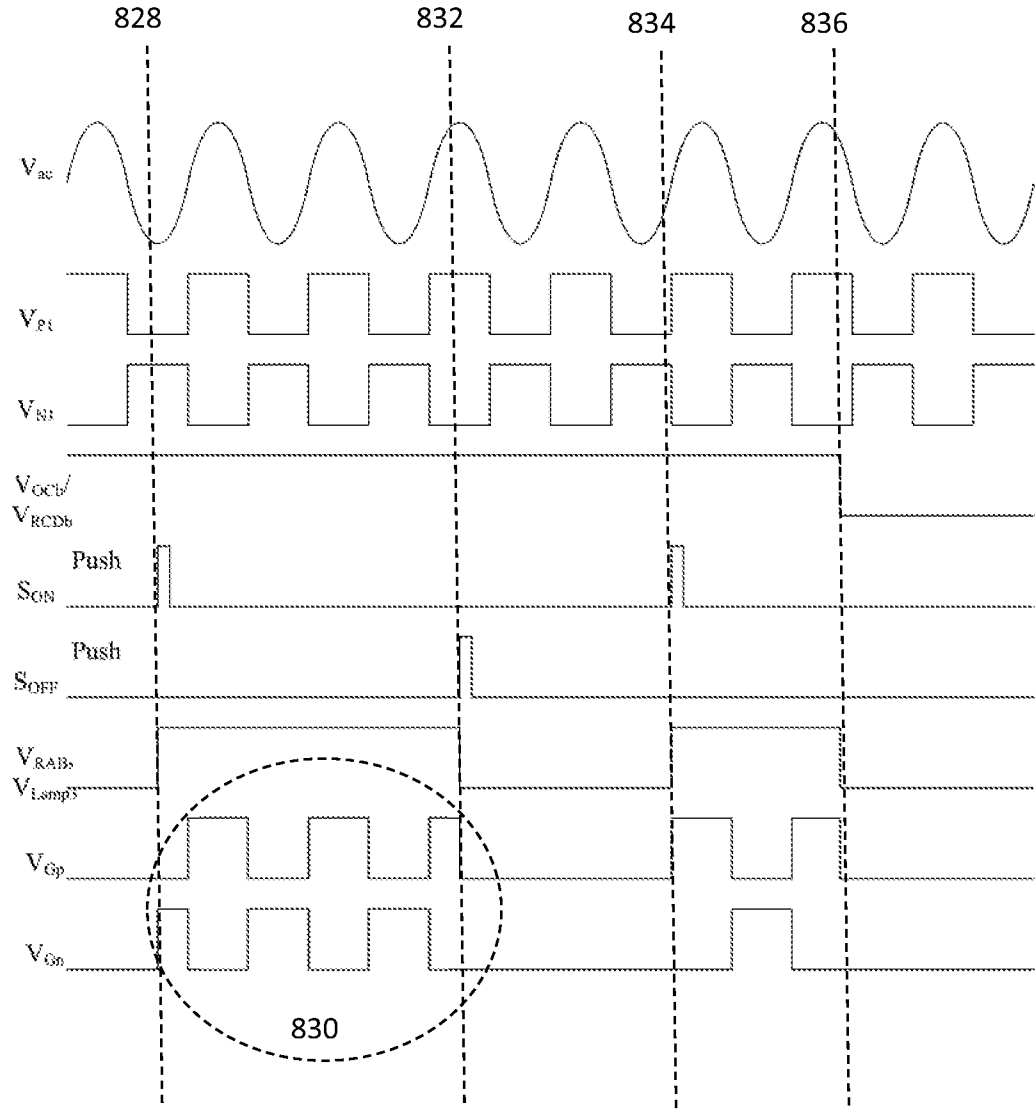


FIG. 8b

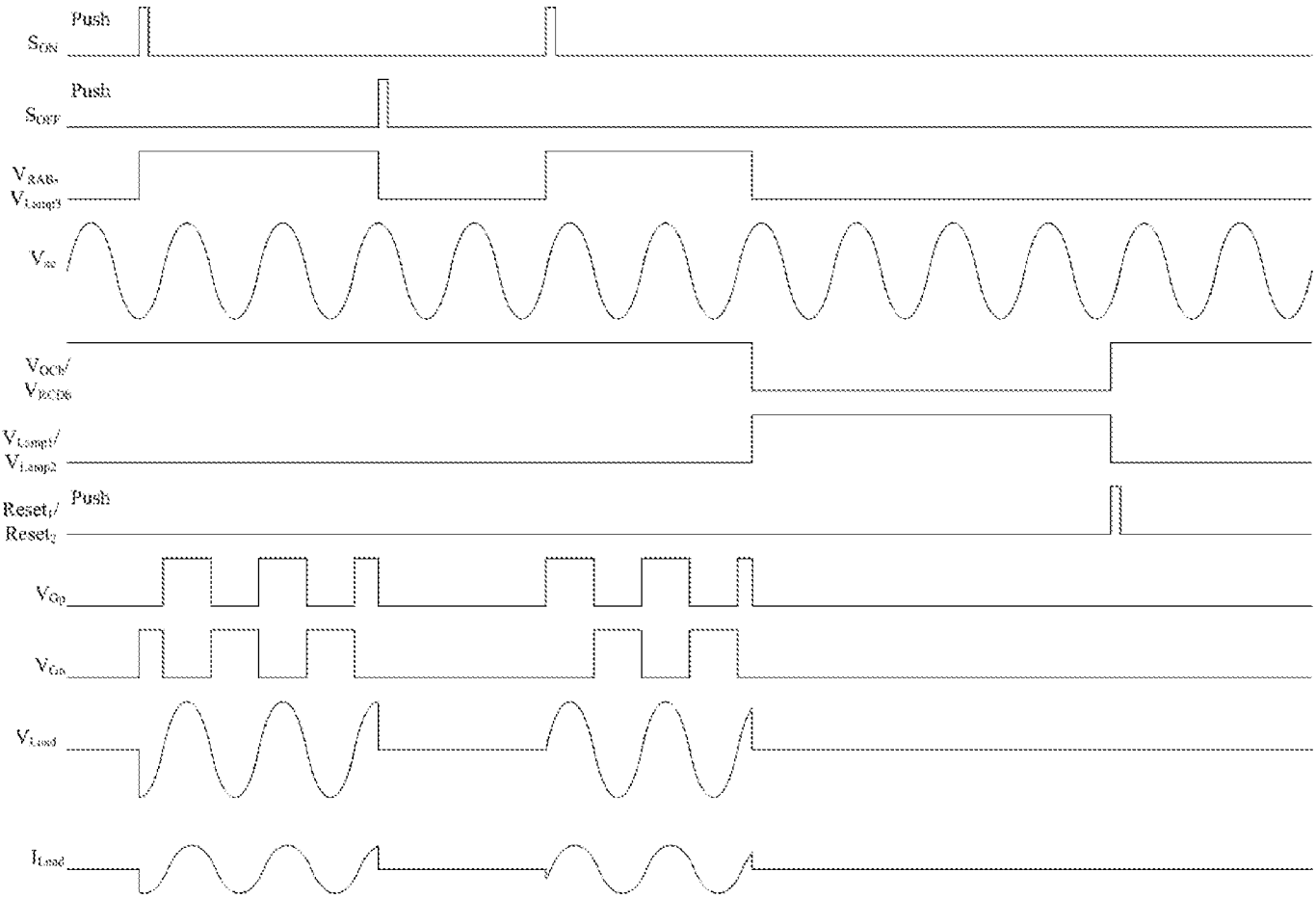


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2017/076671

A. CLASSIFICATION OF SUBJECT MATTER H02H 3/16(2006.01)i; H02H 3/08(2006.01)i 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) H02H; H01H 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) CNPAT, CNKI, EPODOC, WPI: breaker, HF, high frequency, leakage, over current, over load, residual current, electric shock, switch, sensor, detector, transducer, comparator, OP, amplifier																				
C. DOCUMENTS CONSIDERED TO BE RELEVANT <table border="1"> <thead> <tr> <th>Category*</th> <th>Citation of document, with indication, where appropriate, of the relevant passages</th> <th>Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>X</td> <td>CN 2338898 Y (ZHONGHE ELECTRIC APPLIANCE FACTORY) 15 September 1999 (1999-09-15) description, pages 1-2 and figure 1</td> <td>1-22</td> </tr> <tr> <td>X</td> <td>CN 2629306 Y (LIU, ZHENGXING) 28 July 2004 (2004-07-28) description, pages 3-4 and figures 1-2</td> <td>1-22</td> </tr> <tr> <td>X</td> <td>CN 102946083 A (STATE GRID CORP. CHINA ET AL.) 27 February 2013 (2013-02-27) description, paragraphs [0027]-[0051] and figures 1, 3, 7-9</td> <td>1-22</td> </tr> <tr> <td>A</td> <td>JP 07296708 A (MATSUSHITA ELECTRIC WORKS LTD.) 10 November 1995 (1995-11-10) the whole document</td> <td>1-22</td> </tr> <tr> <td>A</td> <td>CN 101950945 A (GUO, LEMING) 19 January 2011 (2011-01-19) the whole document</td> <td>1-22</td> </tr> </tbody> </table>			Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X	CN 2338898 Y (ZHONGHE ELECTRIC APPLIANCE FACTORY) 15 September 1999 (1999-09-15) description, pages 1-2 and figure 1	1-22	X	CN 2629306 Y (LIU, ZHENGXING) 28 July 2004 (2004-07-28) description, pages 3-4 and figures 1-2	1-22	X	CN 102946083 A (STATE GRID CORP. CHINA ET AL.) 27 February 2013 (2013-02-27) description, paragraphs [0027]-[0051] and figures 1, 3, 7-9	1-22	A	JP 07296708 A (MATSUSHITA ELECTRIC WORKS LTD.) 10 November 1995 (1995-11-10) the whole document	1-22	A	CN 101950945 A (GUO, LEMING) 19 January 2011 (2011-01-19) the whole document	1-22
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Date of the actual completion of the international search 09 June 2017		Date of mailing of the international search report 21 June 2017																		
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2017/076671

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
CN	2338898	Y	15 September 1999	None			
CN	2629306	Y	28 July 2004	None			
CN	102946083	A	27 February 2013	CN	102946083	B	10 December 2014
JP	07296708	A	10 November 1995	None			
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