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Liu et al.

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(54) **AUXILIARY CIRCUIT FOR MICRO-ELECTROMECHANICAL SYSTEM RELAY CIRCUIT**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,360,744 A 11/1982 Taylor
4,700,083 A 10/1987 Raets
(Continued)

FOREIGN PATENT DOCUMENTS

EP 1930922 A2 6/2008
EP 2065770 A1 6/2009
(Continued)

OTHER PUBLICATIONS

PCT Search Report and Written Opinion issued in connection with Related PCT Application No. PCT/US2016/057483 dated Jan. 27, 2017.

(Continued)

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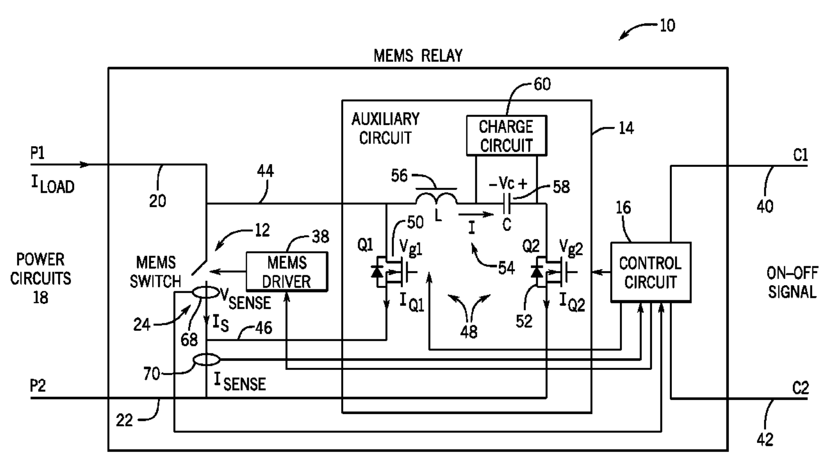
(57) **ABSTRACT**

A switching system includes a MEMS switching circuit having a MEMS switch and a driver circuit. An auxiliary circuit is coupled in parallel with the MEMS switching circuit, the auxiliary circuit comprising first and second connections that connect the auxiliary circuit to the MEMS switching circuit on opposing sides of the MEMS switch, first and second solid state switches connected in parallel, and a resonant circuit connected between the first and second solid state switches. A control circuit controls selective switching of a load current towards the MEMS switching circuit and the auxiliary circuit by selectively activating the first and second solid state switches and the resonant circuit so as to limit a voltage across the MEMS switch by diverting at least a portion of the load current away from the MEMS switch to flow to the auxiliary circuit prior to the MEMS switch changing state.

24 Claims, 7 Drawing Sheets



(51) **Int. Cl.**
H01H 9/54 (2006.01)
H01H 71/00 (2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,949,669 A	9/1999	Bruckmann et al.	
6,034,448 A	3/2000	Xu et al.	
6,094,116 A	7/2000	Tai et al.	
6,201,678 B1*	3/2001	Kolbas	H01H 9/42 361/5
6,490,174 B1	12/2002	Kompelien	
6,643,112 B1	11/2003	Carton et al.	
7,339,288 B2	3/2008	Schasfoort	
7,464,459 B1	12/2008	Niblock et al.	
7,612,971 B2	11/2009	Premerlani et al.	
7,737,810 B2	6/2010	Chan et al.	
7,903,382 B2	3/2011	Premerlani et al.	
8,378,766 B2	2/2013	Lee et al.	
2007/0139831 A1	6/2007	Wright et al.	
2008/0164961 A1	7/2008	Premerlani et al.	
2008/0190748 A1	8/2008	Arthur et al.	
2009/0272634 A1*	11/2009	Ehlers	H01H 59/0009 200/181

FOREIGN PATENT DOCUMENTS

EP	2541568 A1	1/2013
WO	2008153578 A1	12/2008

OTHER PUBLICATIONS

U.S. Appl. No. 14/919,797, filed Oct. 22, 2015, Yanfei Liu et al.

Lee et al. "Integrated Microrelays: Concept and Initial Results", Journal of Microelectromechanical Systems, vol. No. 11, No. 2, pp. 147-153, Apr. 2002.

PCT Search Report and Written Opinion issued in connection with Corresponding PCT Application No. PCT/US2016/50883 dated Dec. 6, 2016.

Keimel et al., "Microelectromechanical-Systems-Based Switches for Power Applications," IEEE Transactions on Industry Applications, vol. 48 , No. 4, Jul.-Aug. 2012, pp. 1163-1169.

* cited by examiner

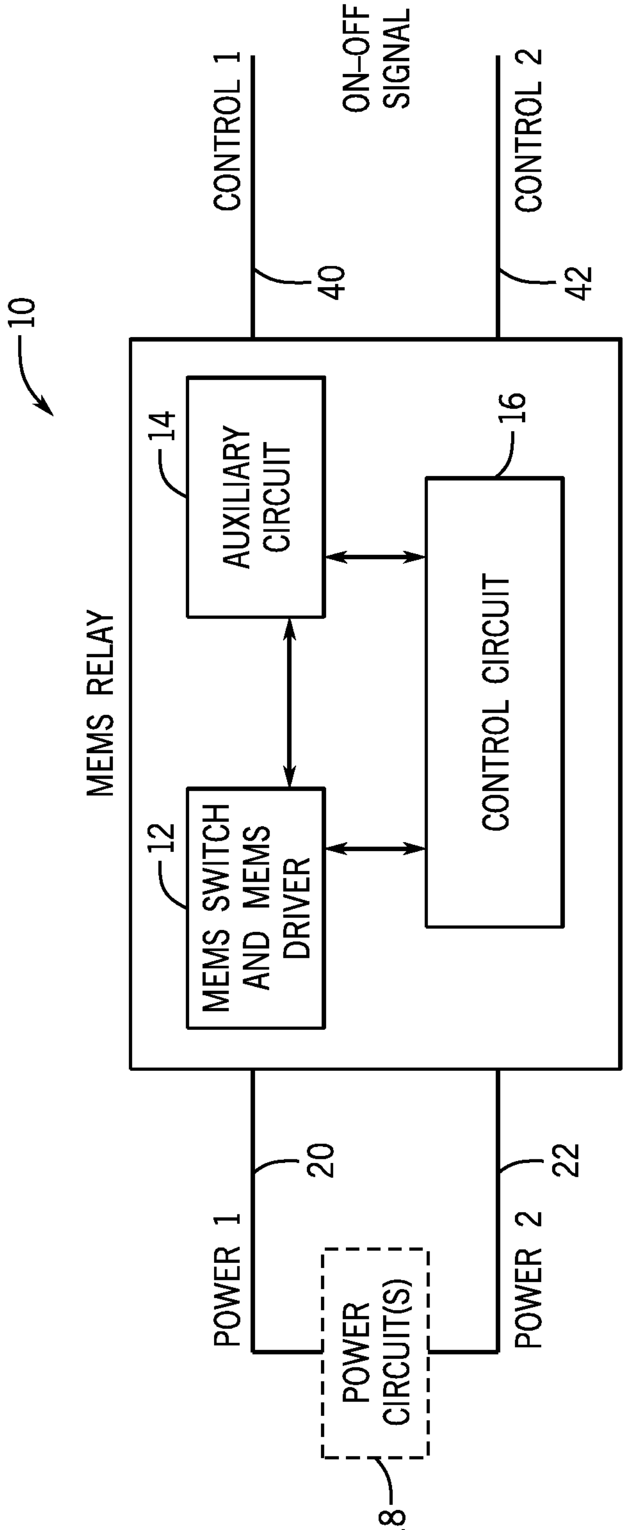

CONTROL 1
ON–OFF SIGNAL
CONTROL 2
40
42
10
MEMS RELAY
14
AUXILIARY CIRCUIT
16
CONTROL CIRCUIT
12
MEMS SWITCH AND MEMS DRIVER
20
22
POWER 1
POWER 2
POWER CIRCUIT(S)
18

FIG. 1

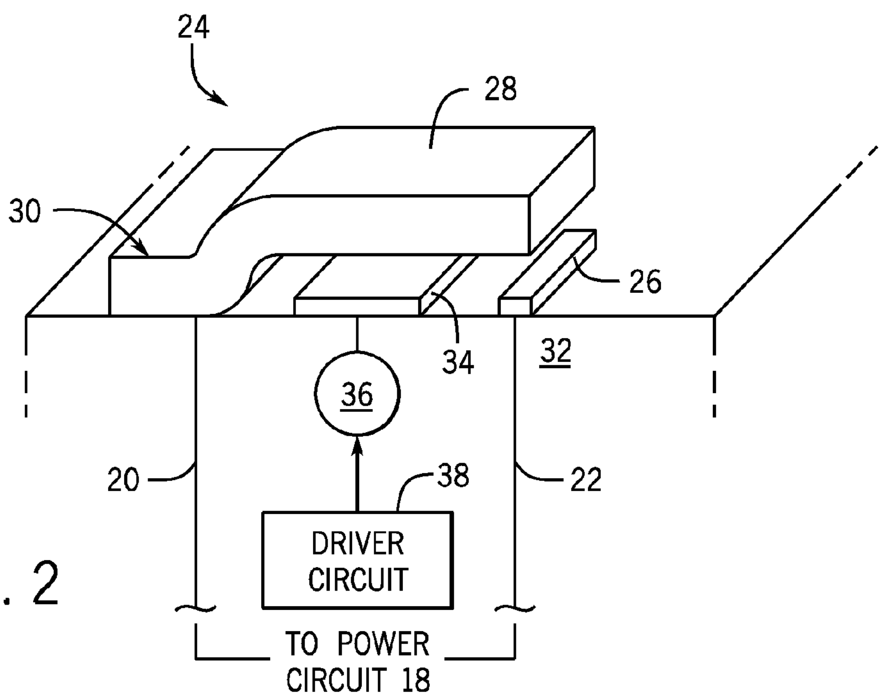


FIG. 2

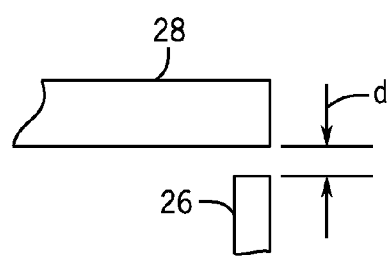


FIG. 3

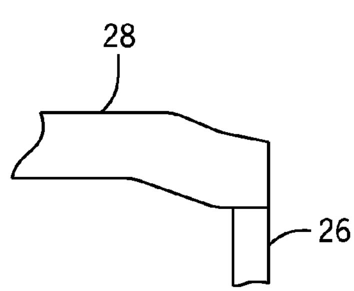
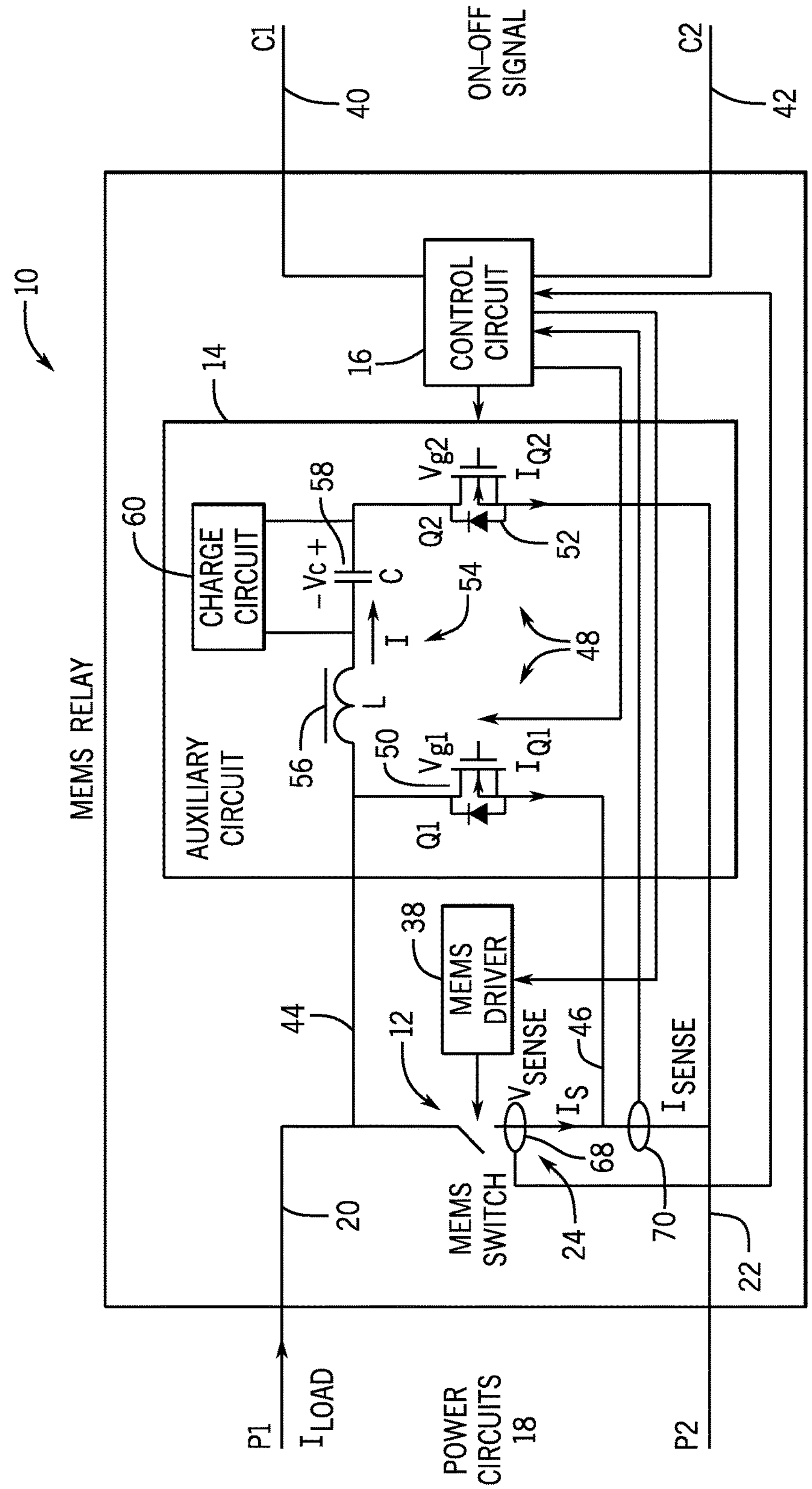


FIG. 4



C1
40
ON-OFF SIGNAL
C2
42
10
CONTROL CIRCUIT
16
14
MEMS RELAY
AUXILIARY CIRCUIT
CHARGE CIRCUIT
60
58
-Vc +
C
L
56
I
54
48
Q1
Q2
Vg1
Vg2
IQ1
IQ2
50
52
MEMS DRIVER
38
44
12
46
VSENSE
IS
ISENSE
MEMS SWITCH
68
24
70
20
22
P1
ILOAD
POWER CIRCUITS 18
P2

FIG. 5

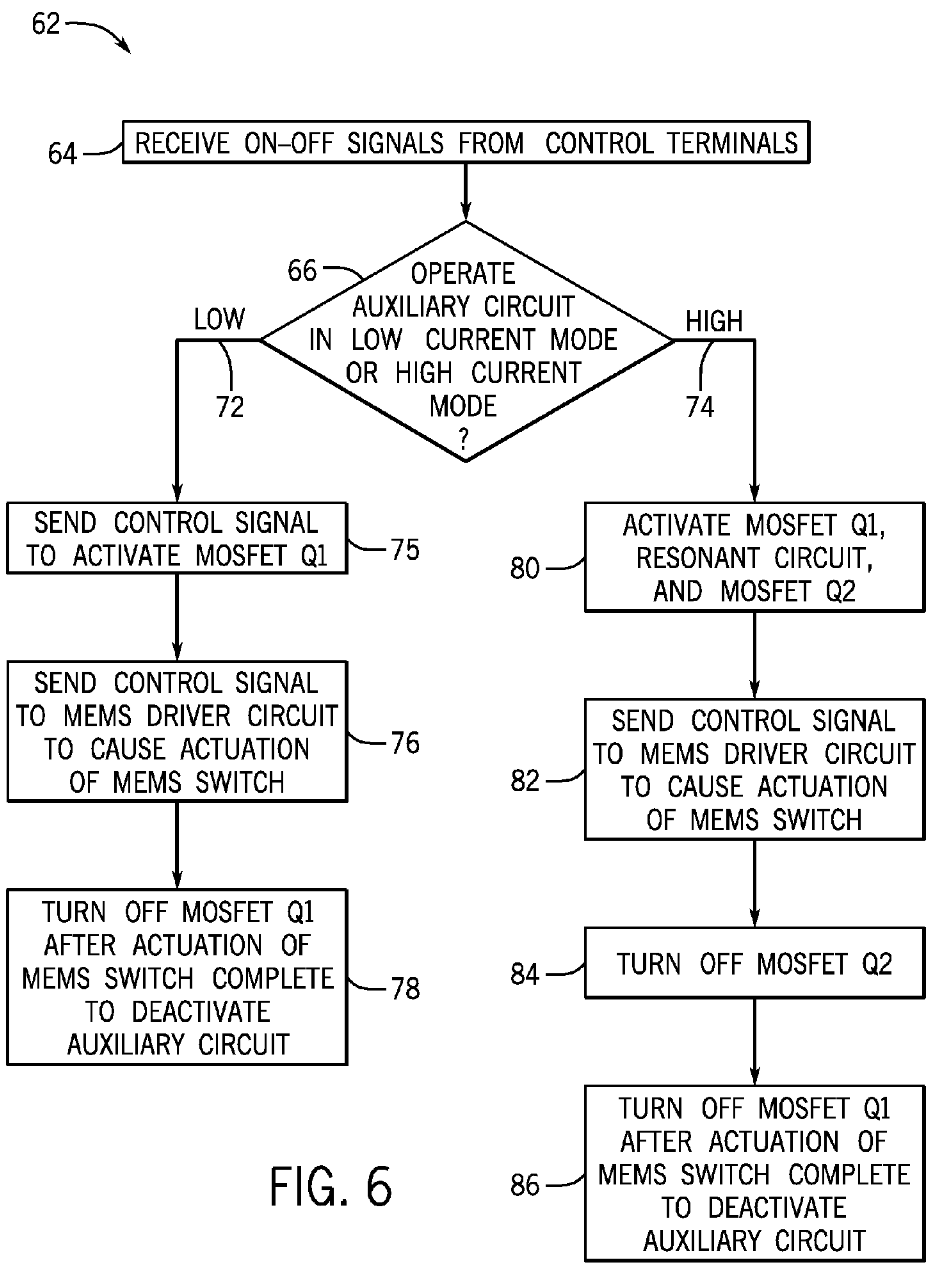

62
64
RECEIVE ON-OFF SIGNALS FROM CONTROL TERMINALS
66
OPERATE AUXILIARY CIRCUIT IN LOW CURRENT MODE OR HIGH CURRENT MODE ?
LOW
HIGH
72
74
SEND CONTROL SIGNAL TO ACTIVATE MOSFET Q1
75
SEND CONTROL SIGNAL TO MEMS DRIVER CIRCUIT TO CAUSE ACTUATION OF MEMS SWITCH
76
TURN OFF MOSFET Q1 AFTER ACTUATION OF MEMS SWITCH COMPLETE TO DEACTIVATE AUXILIARY CIRCUIT
78
80
ACTIVATE MOSFET Q1, RESONANT CIRCUIT, AND MOSFET Q2
82
SEND CONTROL SIGNAL TO MEMS DRIVER CIRCUIT TO CAUSE ACTUATION OF MEMS SWITCH
84
TURN OFF MOSFET Q2
86
TURN OFF MOSFET Q1 AFTER ACTUATION OF MEMS SWITCH COMPLETE TO DEACTIVATE AUXILIARY CIRCUIT

FIG. 6

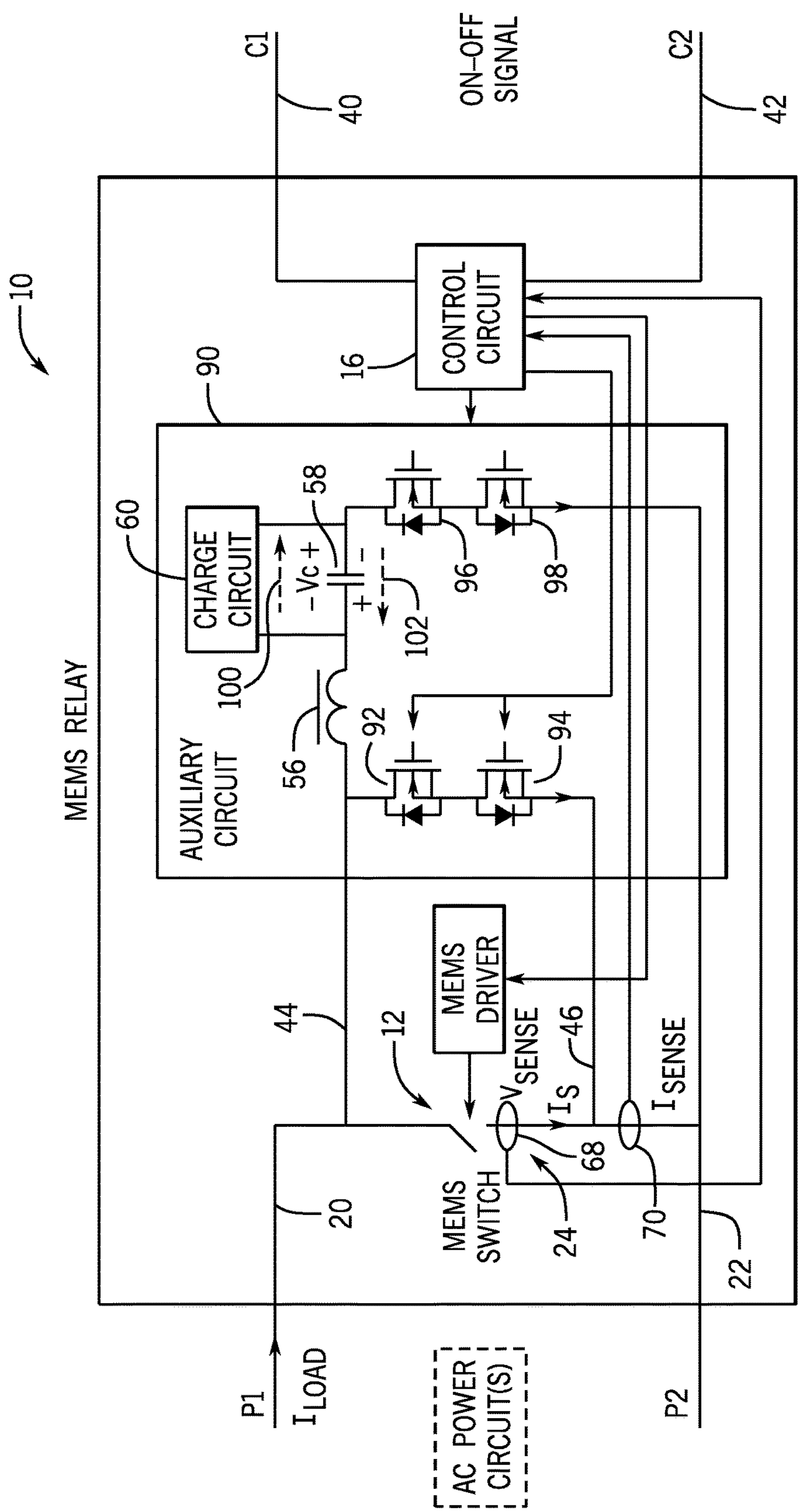
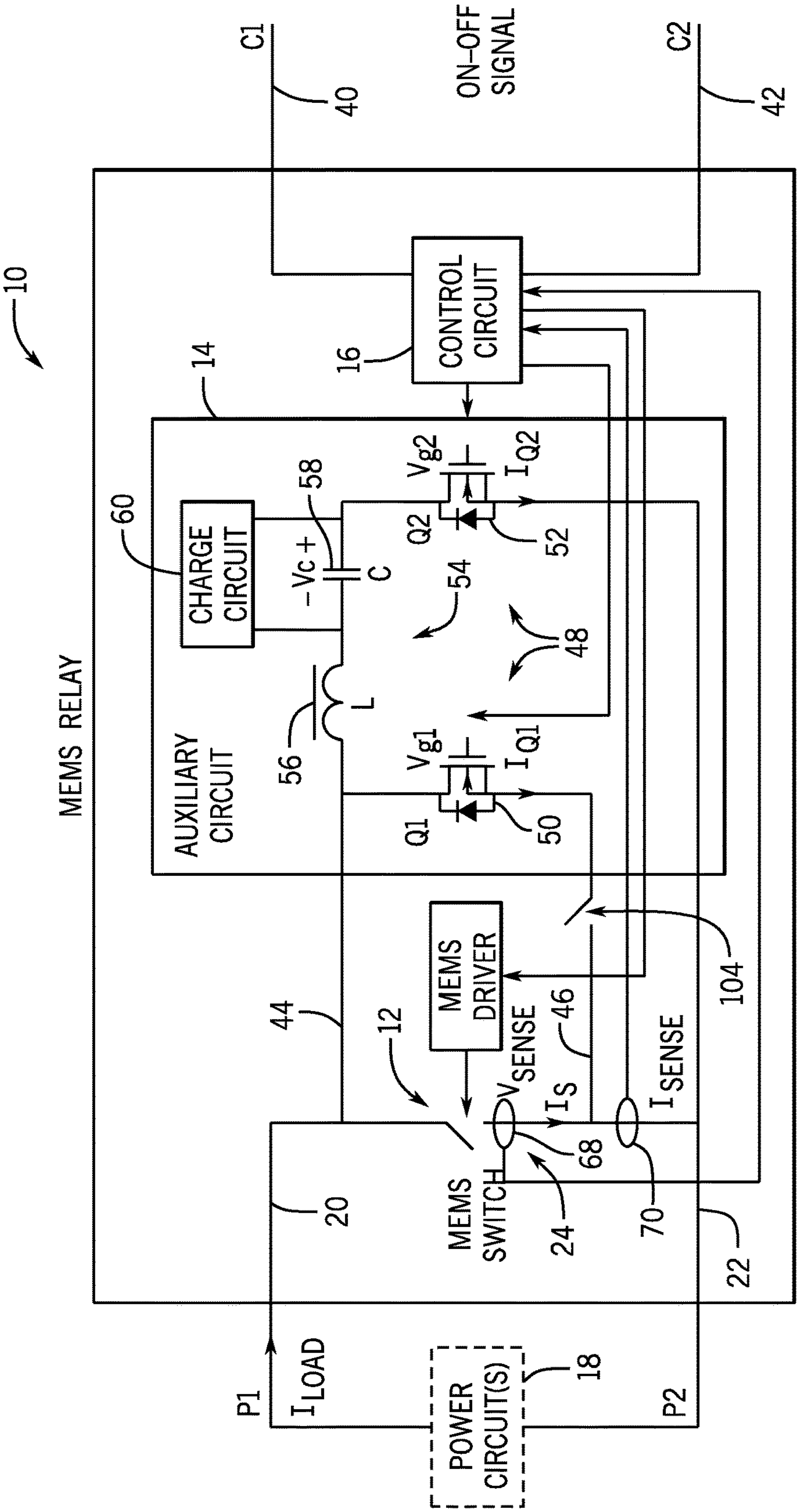

C1
ON-OFF SIGNAL
C2
40
42
10
MEMS RELAY
CONTROL CIRCUIT
16
90
60
CHARGE CIRCUIT
58
Vc
96
98
102
100
56
92
94
AUXILIARY CIRCUIT
MEMS DRIVER
44
12
V_{SENSE}
46
I_S
I_{SENSE}
MEMS SWITCH
68
20
24
70
22
P1
I_{LOAD}
AC POWER CIRCUIT(S)
P2

FIG. 7



C1
ON–OFF SIGNAL
C2
40
42
10
MEMS RELAY
CONTROL CIRCUIT
16
14
CHARGE CIRCUIT
60
58
–Vc +
C
Vg2
IQ2
Q2
52
54
48
L
56
Vg1
IQ1
Q1
50
AUXILIARY CIRCUIT
MEMS DRIVER
104
44
12
VSENSE
46
IS
ISENSE
68
24
70
MEMS SWITCH
20
22
P1
ILOAD
POWER CIRCUIT(S)
18
P2

FIG. 8

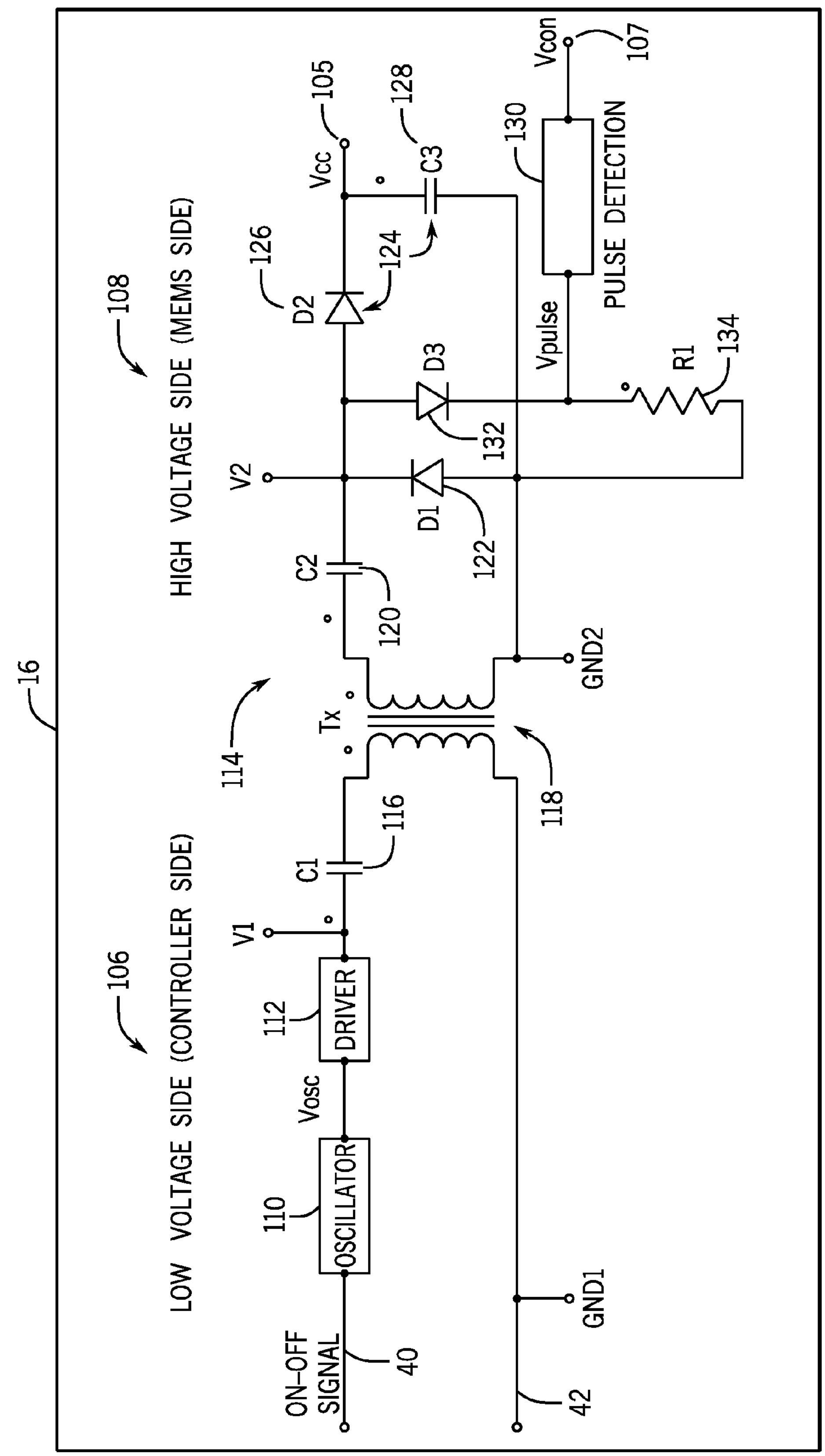

16
LOW VOLTAGE SIDE (CONTROLLER SIDE)
106
HIGH VOLTAGE SIDE (MEMS SIDE)
108
ON-OFF SIGNAL
40
OSCILLATOR
110
Vosc
DRIVER
112
V1
C1
116
Tx
114
118
C2
120
V2
D1
122
D3
132
D2
126
124
Vcc
105
C3
128
130
PULSE DETECTION
Vpulse
R1
134
Vcon
107
GND1
GND2
42

FIG. 9

AUXILIARY CIRCUIT FOR MICRO-ELECTROMECHANICAL SYSTEM RELAY CIRCUIT

BACKGROUND OF THE INVENTION

Embodiments of the invention relate generally to a switching system for On-Off switching of a current in a current path, and more particularly to micro-electromechanical system (MEMS) based switching devices.

Relays are electrically operated switches used to selectively control the flow of current between circuits so as to provide electrical isolation between a control circuit and one or more controlled circuits. Various types of relays are known and may be utilized based on the system and environment in which the relay is implemented, with electromechanical relays and solid-state relays being two common types of relays.

Electromechanical relays are switching devices typically used to control high power devices. Such relays generally comprise two primary components—a movable conductive cantilever beam and an electromagnetic coil. When activated, the electromagnetic coil exerts a magnetic force on the beam that causes the beam to be pulled toward the coil, down onto an electrical contact, closing the relay. In one type of structure, the beam itself acts as the second contact and a wire, passing current through the device. In a second type of structure, the beam spans two contacts, passing current only through a small portion of itself. Electromechanical relays beneficially provide the ability to withstand momentary overload and have a low "on" state resistance. However, conventional electromechanical relays may be large in size may and thus necessitate use of a large force to activate the switching mechanism. Additionally, electromechanical relays generally operate at relatively slow speeds and, when the beam and contacts of the relay are physically separated, an arc can sometimes form therebetween, which arc allows current to continue to flow through the relay until the current in the circuit ceases, while damaging the contacts.

Solid-state relays (SSR) are an electronic switching device that switches on or off when a small external voltage is applied across its control terminals. SSRs include a sensor which responds to an appropriate input (control signal), a solid-state electronic switching device (e.g., thyristor, transistor, etc.) which switches power to the load circuitry, and a coupling mechanism to enable the control signal to activate the switch without mechanical parts. SSRs beneficially provide fast switching speeds compared with electromechanical relays and have no physical contacts to wear out (i.e., no moving parts), although it is recognized that SSRs have a lower ability to withstand momentary overload, compared with electromechanical contacts, and have a higher "on" state resistance. Additionally, since solid-state switches do not create a physical gap between contacts when they are switched into a non-conducting state, they experience leakage current when nominally non-conducting. Furthermore, solid-state switches operating in a conducting state experience a voltage drop due to internal resistances. Both the voltage drop and leakage current contribute to power dissipation and the generation of excess heat under normal operating circumstances, which may be detrimental to switch performance and life and/or necessitate the use of large, expensive heat sinks when passing high current loads.

Micro-electromechanical systems relays (MEMS relays) have been proposed as an alternative to SSRs with most of the benefits of conventional electromechanical relays but sized to fit the needs of modern electronic systems. However, prior MEMS relays are overly complex and may not adequately limit voltage across the movable switch thereof, such that operation of the MEMS relay may not be reliable.

Therefore, it is desirable to provide a MEMS relay circuit that provides/offers much smaller size, much lower power dissipation, longer life, and less contact resistance than electromechanical relays and that provides/offers lower conduction loss and lower cost than SSRs. It is further desirable that such a MEMS relay circuit provide reliable performance without an overly complex structure.

BRIEF DESCRIPTION OF THE INVENTION

In accordance with one aspect of the invention, a switching system includes a MEMS switching circuit including a MEMS switch and a driver circuit, the MEMS switching circuit connectable to a power circuit to receive a load current therefrom. The switching system also includes an auxiliary circuit coupled in parallel with the MEMS switching circuit, the auxiliary circuit comprising first and second connections that connect the auxiliary circuit to the MEMS switching circuit on opposing sides of the MEMS switch, a first solid state switch, a second solid state switch connected in parallel with the first solid state switch, and a resonant circuit connected between the first solid state switch and the second solid state switch. The switching system further includes a control circuit operably connected to the MEMS switching circuit and the auxiliary circuit to control selective switching of a load current towards the MEMS switching circuit and the auxiliary circuit, with the first solid state switch, the second solid state switch and the resonant circuit being selectively activated by the control circuit to divert at least a portion of the load current away from the MEMS switch to flow to the auxiliary circuit.

In accordance with another aspect of the invention, a MEMS relay circuit includes a MEMS switching circuit having a MEMS switch moveable between an open position and a closed position to selectively pass a load current therethrough and a driver circuit configured to provide a drive signal to cause the MEMS switch to move between the open and closed positions. The MEMS relay circuit also includes an auxiliary circuit connected in parallel with the MEMS switching circuit to selectively limit a voltage across the MEMS switch, the auxiliary circuit comprising a first MOSFET and a second MOSFET connected in parallel. The MEMS relay circuit further includes a control circuit operably connected to the MEMS switching circuit and the auxiliary circuit to control switching of the MEMS switch and activation of the first and second MOSFETs in the auxiliary circuit. The auxiliary circuit is selectively operable in a low current mode and a high current mode to selectively allow current flow through the first and second MOSFETs, with the first MOSFET being on and the second MOSFET being off in the low current mode and with the first MOSFET and the second MOSFET being on in the high current mode.

In accordance with yet another aspect of the invention, a method of controlling a micro-electromechanical system (MEMS) relay circuit that includes a MEMS switching circuit, an auxiliary circuit and a control circuit is provided. The method includes receiving at the control circuit one of an Off signal and an On signal comprising a desired operating condition of the MEMS relay circuit. The method also includes sending a driver control signal from the control circuit to a driver circuit of the MEMS switching circuit responsive to the received Off or On signal, the driver control signal causing the driver circuit to selectively provide a voltage to a MEMS switch of the MEMS switching circuit so as to actuate the MEMS switch between a contacting position or non-contacting position. The method further includes sending an auxiliary circuit control signal from the control circuit to the auxiliary circuit responsive to the received Off or On signal, the auxiliary circuit control signal causing the auxiliary circuit to operate in a low current mode or a high current mode to selectively allow current flow through parallelly connected first and second MOSFETs in the auxiliary circuit.

Various other features and advantages will be made apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate embodiments presently contemplated for carrying out the invention.

In the drawings:

FIG. **1** is a block schematic diagram of a MEMS relay circuit in accordance with an exemplary embodiment of the invention.

FIG. **2** is a schematic perspective view of a MEMS switch useable in the MEMS relay circuit of FIG. **1** in accordance with an exemplary embodiment.

FIG. **3** is a schematic side view of the MEMS switch of FIG. **2** in an open position.

FIG. **4** is a schematic side view of the MEMS switch of FIG. **2** in a closed position.

FIG. **5** is a schematic view of an auxiliary circuit useable in the MEMS relay circuit of FIG. **1** in accordance with an exemplary embodiment.

FIG. **6** is a flowchart illustrating a technique for operating the auxiliary circuit of FIG. **5** in a low current mode and high current mode of operation in accordance with an exemplary embodiment

FIG. **7** is a schematic view of an auxiliary circuit useable in the MEMS relay circuit of FIG. **1** in accordance with an exemplary embodiment.

FIG. **8** is a schematic view of an auxiliary circuit useable in the MEMS relay circuit of FIG. **1** in accordance with an exemplary embodiment.

FIG. **9** is a schematic view of a control circuit useable in the MEMS relay circuit of FIG. **1** in accordance with an exemplary embodiment.

DETAILED DESCRIPTION

Embodiments of the invention provide a MEMS relay circuit having an arrangement of a MEMS switch, auxiliary circuit, and control circuit, with the auxiliary circuit and MEMS switch being controlled such that the MEMS relay circuit operates with high efficiency and reliability.

Embodiments of the invention are described below as utilizing MEMS technology; however, it is recognized that such a description is not meant to limit the scope of the invention. That is, MEMS generally refer to micron-scale structures that for example can integrate a multiplicity of functionally distinct elements, for example, mechanical elements, electromechanical elements, sensors, actuators, and electronics, on a common substrate through micro-fabrication technology. It is contemplated, however, that many techniques and structures presently available in MEMS devices will in just a few years be available via nanotechnology-based devices, for example, structures that may be smaller than 100 nanometers in size. Accordingly, even though example embodiments described throughout this document may refer to MEMS-based switching devices, it is submitted that the inventive aspects of the present invention should be broadly construed and should not be limited to micron-sized devices.

Additionally, while embodiments of the invention are described below as being incorporated into relay circuits, it is recognized that such descriptions are not meant to limit the scope of the invention. Instead, it is to be understood that embodiments of the invention may be realized in both relay and circuit protection applications—with circuit protection applications being utilized for the connection and disconnection of a very high current (around 5 times the rated current). Accordingly, use of the term "relay" or "relay circuit" here below is understood to encompass various types of switching systems employed for switching of a current in a current path.

Referring now to FIG. **1**, a block schematic diagram of a MEMS (Micro-Electromechanical System) relay circuit **10** designed for AC and/or DC applications is illustrated according to an embodiment of the invention. The MEMS relay circuit **10** may be generally described as including MEMS switching circuit **12** (formed of a MEMS switch and an associated driver), an auxiliary circuit **14** to limit the voltage across the MEMS switch when it is turned on and turned off, and a control circuit **16** to ensure proper operation of the MEMS switch. The MEMS relay circuit **10** may be connected to a load circuit/power circuit **18** via first and second power terminals **20**, **22**. The power circuit **18** may be characterized by a load inductance and a load resistance and may include a power source (not shown) that provides a voltage V_{LOAD} and a power circuit current I_{LOAD}—with the MEMS switching circuit **12** being selectively controlled to provide for current flow through the power circuit **18**.

A more detailed view of the MEMS switch (and the operation thereof) included in MEMS switching circuit **12** is shown in FIGS. **2-4**. The exemplary MEMS switch **24** includes a contact **26**, which at least partially comprises a conductive material (e.g., a metal), as well as a conductive element, illustrated as a cantilevered beam **28**, comprising conductive material (e.g., a metal). The contact **26** and beam **28** may be formed as a micro-electromechanical or nano-electromechanical device with dimensions on the order of ones or tens of nanometers or micrometers. A cantilevered portion of the beam **28** extends over the contact **26**, with the beam **28** being supported by an anchor structure **30** from which the cantilevered portion extends. The anchor structure **30** serves to connect the cantilevered portion of the beam **28** to an underlying support structure, such as the illustrated substrate **32**.

The MEMS switch **24** also includes an electrode **34** that, when appropriately charged, provides a potential difference between the electrode **34** and the beam **28**, resulting in an electrostatic force that pulls the beam toward the electrode and against the contact **26**. That is, the electrode **34** may act as a "gate" with respect to the MEMS switch **24**, with voltages (referred to as "gate voltages," V_G) being applied to the electrode **34** from a gate voltage source **36**. As the electrode **34** is charged, a potential difference is established between the electrode **34** and the beam **28**, and an electrostatic actuating force acts to pull the beam **28** towards the electrode **34** (and also towards the contact **26**) serving to control the opening or closing of the MEMS switch **24**. With application of sufficient voltage to the electrode **34**, the electrostatic force deforms the beam **28** and thereby displaces the beam from a non-contacting (i.e., open or non-conducting) to a contacting (i.e., closed or conducting).

Movement of the beam **28** between the non-contacting or "open" position and the contacting or "closed" position is shown in FIGS. **3** and **4**. In the non-contacting or open position shown in FIG. **3**, the beam **28** is separated from the contact **26** by a separation distance d, while in the contacting or "closed" position, shown in FIG. **5**, the beam **28** comes into electrical contact with the contact **26**.

During a switching event (i.e., a movement of the MEMS switch **24** from a non-conducting state to a conducting state or vice versa), the gate voltage V_G provided by gate voltage source **36** may be varied over a switching event time or "switching interval," with a driver circuit **38** functioning to control operation of the gate voltage source **36** in providing the gate voltage. For switching events in which the MEMS switch **24** is being opened, the gate voltage would be decreased over the switching interval, while for switching events in which the MEMS switch **24** is being closed, the gate voltage V_G would be increased over the switching interval. In an exemplary embodiment, the switching interval is approximately 10 microseconds or less in duration.

The contact **26** and beam **28** can be respectively connected to either of the power terminals **20**, **22** of the power circuit **18**, such that deformation of the beam **28** between the first and second positions acts to respectively pass and interrupt a current therethrough. The beam **28** may be repeatedly moved into and out of contact with the contact **26** at a frequency (either uniform or non-uniform) that is determined by the application for which the MEMS switch **24** is utilized. When the contact **26** and the beam **28** are separated from one another, the voltage difference between the contact and beam is referred to as the "stand-off voltage." Due to the design of the MEMS switch **24**, the leakage current between power terminals **20**, **22** will be extremely low, e.g., in the pico-Ampere range.

It is noted that while the MEMS switch structure referenced above is described in terms of a solitary MEMS switch **24** having a single moveable element, the MEMS switch structure may include an array of MEMS switches connected in parallel, in series, or both, where each switch of the array includes a moveable element. It is also noted that the MEMS switch structure referenced in FIG. **1** describes an electrical architecture where the conductive path of a closed switch is through the length of the movable element, but it is recognized that other switch architectures can exist where the movable MEMS switch element shunts two separate, planar and isolated conductive paths. As such, references throughout to "a MEMS switch" (e.g., MEMS switch **24**) should be understood to refer to either a single switch or a switch array.

Referring back now to FIG. **1**, and with continued reference to FIGS. **2-4**, according to embodiments of the invention, the auxiliary circuit **14** and control circuit **16** are provided in the MEMS relay circuit **10** in order to provide for operation of the MEMS switch **24** at acceptable voltage and energy levels that increase switching efficiency and switch protection/longevity. That is, the auxiliary circuit **14** (via controlling thereof by control circuit **16**) functions to prevent the MEMS switch **24** from operating in a "hot switching" condition that could negatively impact the switching efficiency and switch longevity. It is recognized that the voltage and energy levels present across the MEMS switch **24** during switching thereof that are deemed to be acceptable can vary based on the function performed by the switch and the number of cycles/switching operations which the switch is desired to be able to withstand (i.e., an expected switch longevity. For example, for a MEMS switch **24** implemented as part of a circuit breaker, where a lifespan of 10,000-100,000 switch cycles/operations is sufficient, the voltage and energy levels across the switch that are deemed to be acceptable is higher than a switch whose longevity is expected to be a billion or more cycles. Thus, for a MEMS switch **24** implemented as part of a circuit breaker, the auxiliary circuit **14** functions to control voltage and energy levels across the MEMS switch **24** to approximately 10 V and 5 microjoules, respectively, while for a MEMS switch **24** with a greater expected lifespan, the auxiliary circuit **14** functions to control voltage and energy levels across the MEMS switch **24** to approximately 1 V and 50 nanojoules, respectively.

In operation of the MEMS relay circuit **10**, the control circuit **16** receives an On-Off control signal from control terminals **40**, **42** connected thereto, with the On-Off control signal indicating a desired operating condition of the MEMS relay circuit **10**. Responsive to the On-Off control signal, the control circuit **16** transmits a control signal to the driver circuit **38** that causes the driver circuit **38** to selectively provide a voltage (via gate voltage source **36**) to the electrode **34** of the MEMS switch **24**—so as to thereby position the MEMS switch **24** in either the open or closed position. If the control circuit **16** receives an On signal from control terminals **40**, **42**, then a control signal is transmitted to the driver circuit **38** that causes a high gate voltage to be applied to the electrode **34**, thereby causing the MEMS switch **24** to be in the closed position so as to allow current to flow therethrough. If the control circuit **16** receives an Off signal from control terminals **40**, **42**, then a control signal is transmitted to the driver circuit **38** that causes a low gate voltage (or zero voltage) to be applied to the electrode **34**, thereby causing the MEMS switch **24** to be in the open position so as to disconnect the power circuit **18**.

In addition to providing control signals to the driver circuit **38** of the MEMS switching circuit **12**, the control circuit **16** also sends control signals to the auxiliary circuit **14** responsive to the received On-Off control signal. The control signals provided to the auxiliary circuit **14** act to selectively activate and deactivate the auxiliary circuit **14**. More specifically, the control circuit **16** is programmed to send control signals to the auxiliary circuit **14** that cause the auxiliary circuit **14** to be activated during the switching interval of the MEMS switch **24** when moving between the open and closed positions and that cause the auxiliary circuit **14** to be deactivated when the MEMS switch **24** is stationary at the fully open or closed position. Activation of the auxiliary circuit **14** during the switching interval of the MEMS switch **24** when moving between the open and closed positions causes at least a portion of the load current I_{LOAD} to flow toward the auxiliary circuit **14**, which in turn reduces the voltage and energy across the MEMS switch **24** during the switching interval. The voltage across the MEMS switch **24** can be limited by activation of the auxiliary circuit **14** such that the voltage does not exceed a pre-determined voltage threshold. In an exemplary embodiment, and as indicated previously, the pre-determined voltage threshold may be a threshold associated with a "hot switching" condition, with the auxiliary circuit **14** functioning to prevent a voltage and energy level across the MEMS switch **24** during the switching interval from exceeding approximately 1 V and 50 nanojoules or from exceeding approximately 10 V and 5 microjoules, depending on the switch function and implementation. By limiting the voltage across the MEMS switch **24** to a low voltage level, reliable operation of MEMS switch can be assured.

In an exemplary embodiment, a sequence by which the MEMS switch **24** is moved between the open and closed positions and by which the activation/deactivation of the auxiliary circuit **14** is performed is controlled by the control circuit **16** to provide adequate protection to the MEMS switch **24**. When an On-Off control signal is received by the control circuit **16** (indicating that the MEMS switch **24** is to be moved from the open to the closed position or from the closed to the open position), the control circuit **16** first causes the auxiliary circuit **14** to be activated such that at least a portion of the load current is diverted from the MEMS switch **24** to the auxiliary circuit **14**. Upon activation of the auxiliary circuit **14**, the control circuit **16** then causes the driver circuit **38** to provide a controlled voltage to the MEMS switch **24** so as to initiate actuation of the MEMS switch **24** from the open to the closed position or from the closed to the open position—with voltage across the MEMS switch **24** being clamped during the switching movement based on the activation of the auxiliary circuit **14**. After the MEMS switch **24** has moved fully to the open position or the closed position—which may be detected based on feedback provided to the control circuit **16** regarding the operating conditions of the MEMS switch **24**—the control circuit **16** then causes the auxiliary circuit **14** to be deactivated, such that the full load current is either passed through the closed MEMS switch **24** or the full load voltage is sustained across the open switch contacts **24**.

Referring now to FIG. **5**, a detailed view of an auxiliary circuit **14** useable in the MEMS relay circuit **10** of FIG. **1**, and its connection to MEMS switching circuit **12** and control circuit **16** is shown according to an exemplary embodiment. As shown in FIG. **5**, the auxiliary circuit **14** is connected in parallel with the MEMS switch **24**—with a first connection **44** of the auxiliary circuit **14** connected to the MEMS switch **24** on a side thereof connected to power terminal **20** and with a second connection **46** of the auxiliary circuit **14** connected to the MEMS switch **24** on a side thereof connected to power terminal **22**. The auxiliary circuit **14** includes solid state switching circuitry **48** that, in the illustrated embodiment, is composed of a pair of MOSFETs **50**, **52** (also referred to as MOSFETs Q1 and Q2, respectively) arranged in parallel, although it is recognized that other suitable solid state switches could be substituted for the MOSFETs. The auxiliary circuit **14** further includes a resonant circuit **54** (consisting of an inductor **56** and capacitor **58** arranged in series) positioned between the MOSFETs **50**, **52**, as well as a charge circuit **60** for charging the capacitor **58** of the resonant circuit **54**.

The construction of auxiliary circuit **13** allows it to function in two separate operating modes—low current mode and high current mode—with the selection of the low current or high current mode dependent on the magnitude of the load current I_{LOAD} provided to the MEMS relay circuit **10** from power circuit **18**. In the low current mode of operation, MOSFET **50** is turned On so as to conduct current therethrough while MOSFET **52** remains in an Off condition such that it is non-conductive. Along with MOSFET **52** being Off, the resonant circuit **54** also is not activated when the auxiliary circuit **14** is in the low current mode. In the high current mode of operation, both of MOSFETs **50** and **52** are turned On so as to conduct current therethrough, and the resonant circuit **54** is activated to draw current from MOSFET **50** and provide resonance. It is noted that when the inductor **56** and capacitor **58** of the resonant circuit **54** operate in a resonant mode, the voltage across them is the conduction voltage of MOSFET **52** and MOSFET **50**, which is very small. Therefore, the peak resonant current can be very high with moderate inductance and capacitance values and with a pre-charged capacitor voltage (charged by charge circuit **60**). By resonance, the pre-charged capacitor voltage will be recovered to a large extent.

A technique implemented by control circuit **16** for operating the auxiliary circuit **14** in the low current mode and high current mode relative to operation of the MEMS switching circuit is shown and described in greater detail in FIG. **6**. Initially in technique **62**, an On-Off signal is received by the control circuit at STEP **64** indicating a desired/required movement of the MEMS switch **24** from the open position to the closed position or from the closed position to the open position. Upon receipt of the On-Off signal by control circuit **16**, a determination is made by control circuit **16** at STEP **66** as to whether the auxiliary circuit **14** is to be operated in the low current mode or the high current mode of operation. In order to make this determination, the control circuit **16** receives feedback from one or more sensing devices that may include a voltage sensor **68** and/or a current sensing circuit **70**, I_{sense}, (see FIG. **5**) that is/are positioned so as to sense a voltage across the MEMS switch **24** (when in the open position) or a current flowing through the MEMS switch **24** (when in the closed position).

When the MEMS switch **24** is in the fully open position (and is to be transitioned to the closed position), the voltage sensor **68** (e.g., comparator) will sense a voltage across MEMS switch **24**. When the MEMS switch **24** is in the fully open position (and is to be transitioned to the closed position), the voltage sensor **68** will sense a voltage across MEMS switch **24**—from which a current may then be calculated The level of voltage sensed by voltage sensor **68** is analyzed by the control circuit **16** in order to determine what the associated current through the switch would be when in the closed position—with a determination then also being made of which auxiliary circuit mode of operation should be employed. That is, if the voltage sensed by the voltage sensor **68** is of a level that when a full load current is passed through MOSFET Q1, an associated voltage drop, V_{ds1}, of MOSFET Q1 is sufficiently low so that the voltage across MEMS switch **24** is also sufficiently low, then the control circuit **16** determines that the auxiliary circuit **14** should be operated in the low current mode of operation, as indicated at STEP **72**. Conversely, if the voltage sensed by the current voltage sensor **68** is of a level that when a full load current is passed through MOSFET Q1, an associated voltage drop, V_{ds1}, of MOSFET Q1 may be too high for reliable operation of the MEMS switch **24** (i.e., the voltage across the MEMS switch **24** may be too high—such as above the hot switching threshold), then the control circuit **16** determines that the auxiliary circuit **14** should be operated in the high current mode of operation. In an alternative embodiment, it is recognized that when the MEMS switch **24** is in the fully open position (and is to be transitioned to the closed position)—rather than sensing a voltage across MEMS switch **24** via voltage sensor **68**—the control circuit **16** could instead simply default to operating the auxiliary circuit **14** in the high current mode.

When the MEMS switch **24** is in the fully closed position (and is to be transitioned to the open position), the current sensing circuit **70** will sense the current flowing through the MEMS switch **24**. The level of current sensed by current sensing circuit **70** is analyzed by the control circuit **16** in order to determine which auxiliary circuit mode of operation should be employed. That is, if the current sensed by the current sensing circuit **70** is of a level that when a full load current is passed through MOSFET Q1, an associated voltage drop, V_{ds1}, of MOSFET Q1 is sufficiently low so that the voltage across MEMS switch **24** is also sufficiently low, then the control circuit **16** determines that the auxiliary circuit **14** should be operated in the low current mode of operation, as indicated at STEP **72**. Conversely, if the current sensed by the current sensing circuit **70** is of a level that when a full load current is passed through MOSFET Q1 an associated voltage drop, V_{ds1}, of MOSFET Q1 may be too high for reliable operation of the MEMS switch **24** (i.e., the voltage across the MEMS switch **24** may be too high—such as above the hot switching threshold), then the control circuit **16** determines that the auxiliary circuit **14** should be operated in the high current mode of operation.

When the control circuit **16** determines at STEP **66** that the auxiliary circuit **14** may be operated in the low current mode of operation (based on feedback from the voltage sensor **68** or current sensing circuit **70**), as indicated at **72**, the control circuit **16** will send control signals to the auxiliary circuit **14** at STEP **75** to cause activation of MOSFET Q1, with activation of MOSFET Q1 allowing current to conduct therethrough. After activation of the MOSFET Q1, the control circuit **16** sends a control signal to the driver circuit **38** at STEP **76** that provides for actuation of the MEMS switch **24**. When the MEMS switch **24** is to be turned/actuated from Off to On, MOSFET Q1 is first turned on such that the load current will flow through MOSFET Q1 (STEP **75**) and the voltage across MEMS switch **24** becomes V_{ds1}, which is the voltage across MOSFET Q1. After MOSFET Q1 has been activated, the MEMS switch **24** is then turned On/closed at STEP **76**—with the voltage across the MEMS switch **24** being controlled below a desired threshold based on the activation of MOSFET Q1. The MOSFET Q1 remains activated until the MEMS switch **24** has completely closed, at which time MOSFET Q1 is turned off at STEP **78**, such that the auxiliary circuit **14** is deactivated. When the MEMS switch **24** is to be turned/actuated from On to Off, MOSFET Q1 is first turned on—with the result being that a small portion of the load current I_{LOAD} will be diverted to the MOSFET Q1 while a majority of the load current still flows through the MEMS switch **24**, as it has a lower On resistance. After the MOSFET Q1 has been fully activated, the MEMS switch **24** is moved to the Off/open position at STEP **76**, with the voltage across the MEMS switch **24** being limited by the On voltage of MOSFET Q1, V_{ds1}. Upon movement of the MEMS switch **24** to the fully open position, an entirety of the load current flows through MOSFET Q1, and the MOSFET Q1 is then turned off at STEP **78** (i.e., the auxiliary circuit **14** is deactivated) and the load current I_{LOAD} is disconnected with the MEMS relay circuit **10** in the Off state.

When the control circuit **16** determines at STEP **66** that the auxiliary circuit **14** should be operated in the high current mode of operation (based on feedback from the current sensing circuit), as indicated at **74**, the control circuit **16** will send control signals to the auxiliary circuit **14** at STEP **80** to cause activation of MOSFET Q1 and activation of the resonant circuit **54** and MOSFET Q2 to reduce the current through MOSFET Q1 and MEMS switch **24**. That is, when the MOSFET Q1 is fully on, the resonant circuit **54** and MOSFET Q2 are then turned on—with the resonant circuit **54** causing resonant current to flow in the direction towards MOSFET Q2 (via pre-charging of the capacitor **58** in the direction toward MOSFET Q2, as shown) so as to reduce the current through MOSFET Q1. After activation of the resonant circuit **54** and MOSFET Q2, the control circuit **16** then sends a control signal to the driver circuit **38** at STEP **82** that provides for actuation of the MEMS switch **24**, with it being recognized that the reduction of current through MOSFET Q1 to an acceptably low level results in an acceptable voltage V_{ds1} across the MOSFET Q1 and a corresponding acceptable voltage level across the MEMS switch **24** that is below a pre-determined threshold during actuation thereof.

In high current mode operation of the auxiliary circuit **14**, when the MEMS switch **24** is to be turned/actuated from Off to On, after activation of the MOSFET Q1 has been performed and the load current I_{LOAD} is flowing therethrough, MOSFET Q2 is then turned on—with the resonant circuit **54** causing resonant current to flow in the direction towards MOSFET Q2 to reduce the current through MOSFET Q1. Upon activation of MOSFET Q2, the resonant current will reduce the current through MOSFET Q1 and therefore reduce the voltage V_{ds1} across MOSFET Q1 to a sufficiently low level, with the MEMS switch **24** then being turned On/closed (STEP **82**)—with the voltage across the MEMS switch **24** being controlled below a desired threshold based on the activation of MOSFETs Q1 and Q2. The MOSFETs Q1 and Q2 remain activated until the MEMS switch **24** has completely closed, at which time MOSFET Q2 is then turned off at STEP **84** (after I_{Q2} reverses direction)—with the resonance stopping after the inductor current becomes zero, i.e., after one resonant period. Upon termination of the resonance, MOSFET Q1 is then turned Off at STEP **86**, such that the auxiliary circuit **14** is fully deactivated.

In high current mode operation of the auxiliary circuit **14**, when the MEMS switch **24** is to be turned/actuated from On to Off, after activation of the MOSFET Q1 has been performed and the load current I_{LOAD} is flowing therethrough, MOSFET Q2 is then turned on—with the resonant circuit **54** causing resonant current to flow in the direction towards MOSFET Q2 to reduce the combined current flowing through the MEMS switch **24** and MOSFET Q1. Upon reduction of the combined current flowing through the MEMS switch **24** and MOSFET Q1 and an accompanying reduction of the voltage level across the MEMS switch **24** and MOSFET Q1 to a sufficiently low level, the MEMS switch **24** is then turned Off/opened at a low voltage (STEP **82**). The MOSFETs Q1 and Q2 remain activated until the MEMS switch **24** has completely opened, at which time MOSFET Q2 is then turned off at STEP **84** (after I_{Q2} reverses direction)—with the resonance stopping after the inductor current becomes zero, i.e., after one resonant period. Upon termination of the resonance, MOSFET Q1 is then turned Off at STEP **86**, such that the auxiliary circuit **14** is fully deactivated and the load current is disconnected with the MEMS relay circuit **10** in the Off state.

The auxiliary circuit **14** shown and described in FIG. **5** is employed with a power circuit **18** connected to MEMS relay circuit **10** that applies a DC power at the power terminals **20**, **22**, and it is recognized that the structure of the auxiliary circuit **14** would be modified when a power circuit is connected to MEMS relay circuit **10** that applies an AC power at the power terminals **20**, **22**. Referring now to FIG. **7**, an auxiliary circuit **90** for use with a power circuit that provides AC power to the MEMS relay circuit **10** is illustrated according to another embodiment. The auxiliary circuit **90** of FIG. **7** differs from the auxiliary circuit **14** of FIG. **5** in that each of the MOSFETs **50** and **52** is replaced by a pair of MOSFETS connected back-to-back—i.e., MOSFETS **92**, **94** and **96**, **98**. In an AC application, the pre-charged capacitor voltage polarity (of capacitor **58**) would be changed at line cycle based on the actual load current I_{LOAD}. For example, when the actual load current is from power terminal **20** to power terminal **22**, the capacitor voltage polarity would be in a first direction, as indicated at **100** in FIG. **7**. In this way, the resonant current would reduce the actual MEMS switch current. When the actual load current flows from power terminal **22** to power terminal **20**, the capacitor voltage polarity would be reversed so as to be in a second direction, as indicated at **102** in FIG. **7**—such that the resonant current would again reduce the actual MEMS switch current. In the auxiliary circuit **90**, the power loss would be very small, as the capacitor value is small, capacitor voltage is also small, and the frequency is low.

Referring now to FIG. **8**, in still another embodiment, the structure of an MEMS relay circuit **10** incorporating the auxiliary circuit **14** shown and described in FIG. **5** is modified to provide for electrical isolation of the auxiliary circuit from the power circuit. To provide such isolation, a MEMS switch **104** would be positioned in series with the auxiliary circuit **14** to selectively connect and disconnect the auxiliary circuit **14** from the power circuit **18**. In an exemplary embodiment, the MEMS switch **104** would be positioned in series with MOSFET **50**—between MOSFET **50** and the second connection **46** of the auxiliary circuit **14**—to open up leakage of the auxiliary circuit **14**.

The auxiliary circuits **14**, **90** illustrated in FIGS. **5**, **7** and **8** beneficially provide a low cost and small option for controlling voltage across the MEMS switching circuit **12**. The auxiliary circuit **14** requires only two MOSFETs **50**, **52**, one inductor **56** and one capacitor **58**. The operation of the auxiliary circuit **14** in one of two operating modes—low current mode or high current mode—allows for flexibility with regard to the On resistance of the MOSFET **50** (i.e., the on resistance does not need to be very small), such that the cost of the MOSFET **50** can be low, and there is no specific requirement for the On resistance of MOSFET **52**. In addition, when the inductor **56** and capacitor **58** operate in resonant mode, the voltage across them is the conduction voltage of MOSFETs **52** and **50**, which is very small, such that the peak resonant current can be very high with moderate inductor and capacitor values and the pre-charge capacitor voltage.

Referring now to FIG. **9**, and with reference back to FIGS. **1** and **5**, a detailed view of a control circuit **16** useable in the MEMS relay circuit **10** of FIG. **1**, and its connection to MEMS switching circuit **12** and auxiliary circuit **14**, is shown according to an exemplary embodiment. The control circuit **16** is configured so as to provide for electrical isolation between control input terminals **40**, **42** and control output terminals **105**, **107** thereof (i.e., from a low voltage “control side” **106** to a high voltage “power side” **108**) and provide the logic circuitry necessary to control a transfer of switching signals power for the MEMS switching circuit **12** and auxiliary circuit **14**. The control circuit **16** provides for transferring of the On-Off control signal (received via control terminals **40**, **42**) and power from the control side **106** of the MEMS relay circuit **10** to the MEMS switching circuit **12** on the power side **108** of the MEMS relay circuit **10**, with the On-Off control signal and power being transferred across an isolation barrier.

As shown in FIG. **9**, the control circuit **16** includes an oscillator **110** that is connected to control terminal **40** and is controlled by the On-Off signals received thereby, with the On-Off signals being logic high-logic low signals. The logic level On-Off signals cause the oscillator **110** to generate an electrical pulse (i.e., a “first electrical pulse”) having a voltage, V_{osc}, and a “first signal characteristic” when the On-Off signal is logic high and a “second signal characteristic” when the On-Off signal is logic low. In one embodiment, the logic level On-Off signals cause the oscillator **110** to generate an electrical pulse at a first frequency F_1 when the On-Off signal is logic high and at a second frequency F_2 when the On-Off signal is logic low. In another embodiment, the logic level On-Off signals cause the oscillator to operate in a PWM (pulse width modulated) mode where the oscillator’s duty cycle would vary (i.e., the pulse width would vary) but its frequency would be constant. That is, when the On-Off signal is a logic high, the oscillator **110** would output an electrical pulse at a first duty cycle, DC_1, (for example 50% duty cycle), and when the On-Off signal is a logic low, the oscillator **110** would output an electrical pulse at a second duty cycle, DC_2, (for example 10% duty cycle). In practice, the PWM mode is preferred since it allows a pulse transformer in the control circuit **16** (as described in further detail below) to be designed for operation at a single frequency, thus simplifying the design. A driver **112** is connected to the oscillator **110** that acts as a low voltage buffer in control circuit **16** and also increases the current driving/carrying capability (i.e., provides a current boost) of the oscillator **110**.

As further shown in FIG. **9**, the control circuit **16** includes a pulse transformer **114** that serves to interface the low-voltage control side **106** to the high-voltage power side **108** (i.e., to gates of the MEMS switch **24** and MOSFETs **50**, **52** (in auxiliary circuit **14**)—and provides an electrical isolation barrier across which control signals and power is transmitted, such as in the form of rectangular electrical pulses (that is, pulses with fast rise and fall times and a relatively constant amplitude). A primary side of the pulse transformer **114** is provided on the low voltage side **106** of the control circuit **16**, while a secondary side of the pulse transformer **114** is provided on the high voltage side **108** of the control circuit **16**. In an exemplary embodiment, the pulse transformer **114** may be constructed to have two windings thereon in order to provide an appropriate level of voltage increase thereacross—such as a conversion from 0-5 V at the control terminal up to 10 V (to drive MOSFETs **50**, **52** in auxiliary circuit) and/or 60-80 V (to drive MEMS switch **24**)—although it is recognized that other numbers of windings could be provided on the transformer. In operation, the pulse transformer **114** receives the first electrical pulse from the oscillator **110** and outputs a “second electrical pulse” having the same signal characteristic as the first electrical pulse provided from the oscillator **110** (i.e., at either the same first frequency or second frequency, or at either the same first duty cycle or second duty cycle), but that is electrically isolated from the first electrical pulse.

Also included in control circuit **16** are a capacitor **116** on the primary side, a capacitor **120** on the secondary side, and a diode **122** on the secondary side. The pulse transformer **114** operates with the arrangement of the capacitor **116**, capacitor **120**, and diode **122** to provide for DC voltage recovery, such that a voltage on the control side, V_1, and a voltage on the power side, V_2, have the same shape (i.e., same frequency and/or duty cycle)—with the voltages V_1 and V_2 being electrically isolated and referenced to different grounds.

Also included in control circuit **16** is a peak voltage detector **124** comprised of a diode **126** and capacitor **128**. The peak voltage detector **124** functions to detect the peak voltage of voltage V_2 and can be used as a power source for all the electronic circuits on the high voltage side **108** of the MEMS relay circuit **10** (MEMS switch side), including the MEMS driver circuit **38**, pulse detection circuits **130**, and other control and driver circuits for the auxiliary circuit **14**—with an output of the peak voltage detector **124**, V_{cc}, being provided to output terminal **105**.

In an exemplary embodiment, an additional diode **132** and resistor **134** in control circuit **16** retrieve the second electrical pulse generated by pulse transformer **114**, the voltage of which is referred to as V_{pulse} in FIG. **9**. After passing through diode **132** and resistor **134**, the second electrical pulse is then provided to a pulse detection circuit **130**. According to embodiments of the invention, the pulse detection circuit **130** may be configured to determine/detect the frequency of the pulse signal—i.e., whether the second electrical pulse is at the first frequency F_1 or the second frequency F_2—or determine/detect the duty cycle (by detecting the pulse width) of the pulse signal—i.e., whether the second electrical pulse is at the first duty cycle DC_1 or the duty cycle DC_2. The pulse detection circuit **130** then subsequently controls transmission of power and control signals to the MEMS switching circuit **12** based on this determination. While control circuit **16** is illustrated as including diode **132** and resistor **134** to retrieve the electrical pulse signal, an alternative version of control circuit **16** could omit these components—as it is possible to connect the voltage V_2 directly into the pulse detection circuit **130**.

In operation, and when configured to determine frequency of the second electrical pulse, the pulse detection circuit **130** detects the frequency of the second electrical pulse output from pulse transformer **114** (which is same as that of V_1). When the pulse detection circuit detects that the frequency of V_{pulse} is a first frequency, F_1, the voltage of a generated control signal, V_{con}, provided to driver circuit **38** (to control the switching of MEMS switch **24**) will be logic high to indicate that the On-Off signal is high—therefore causing the MEMS switch to actuate to the closed position. When the pulse detection circuit **130** detects that the frequency of the second electrical pulse is a second frequency, F_2, the voltage of the generated control signal, V_{con}, provided to driver circuit **38** (to control the switching of MEMS switch **24**) will be logic low to indicate that the On-Off signal is low—therefore causing the MEMS switch to actuate to the open position.

In operation, and when configured to determine the duty cycle of the second electrical pulse, the pulse detection circuit **130** detects the duty cycle of the second electrical pulse output from pulse transformer **114** (which is same as that of V_1). When the pulse detection circuit detects that the duty cycle of V_{pulse} is a first duty cycle, DC_1, the voltage of a generated control signal, V_{con}, provided to driver circuit **38** (to control the switching of MEMS switch **24**) will be logic high to indicate that the On-Off signal is high—therefore causing the MEMS switch to actuate to the closed position. When the pulse detection circuit **130** detects that the duty cycle of the second electrical pulse is a second duty cycle, DC_2, the voltage of the generated control signal, V_{con}, provided to driver circuit **38** (to control the switching of MEMS switch **24**) will be logic low to indicate that the On-Off signal is low—therefore causing the MEMS switch to actuate to the open position.

The control circuit **16** of FIG. **9** beneficially provides electrical isolation between the control side and the power side of the relay circuit—with the MEMS switch and auxiliary circuit receiving control signals on the power side. The control circuit also provides for the transfer of power and the transmission of control signals from a low voltage side to a high voltage side using only one pulse transformer and low cost electronic circuits, such that the control circuit exhibits smaller size, low power dissipation, and simplified circuits, all of which reduces costs associated with the production and use of the MEMS relay circuit.

A technical contribution of embodiments of the invention is that it provides a controller implemented technique for operating a MEMS switch and accompanying auxiliary switch that limits the voltage across the MEMS switch during a switching interval thereof. The control circuit selectively activates the auxiliary circuit during the turning on and turning off time interval of the MEMS switch to divert current to the auxiliary circuit and thereby clamp the voltage across the MEMS switch to a level below that of a pre-determined threshold voltage, while the control circuit deactivates the auxiliary circuit after actuation of the MEMS switch between positions/states is complete.

Therefore, according to one embodiment of the invention, a switching system includes a MEMS switching circuit including a MEMS switch and a driver circuit, the MEMS switching circuit connectable to a power circuit to receive a load current therefrom. The switching system also includes an auxiliary circuit coupled in parallel with the MEMS switching circuit, the auxiliary circuit comprising first and second connections that connect the auxiliary circuit to the MEMS switching circuit on opposing sides of the MEMS switch, a first solid state switch, a second solid state switch connected in parallel with the first solid state switch, and a resonant circuit connected between the first solid state switch and the second solid state switch. The switching system further includes a control circuit operably connected to the MEMS switching circuit and the auxiliary circuit to control selective switching of a load current towards the MEMS switching circuit and the auxiliary circuit, with the first solid state switch, the second solid state switch and the resonant circuit being selectively activated by the control circuit to divert at least a portion of the load current away from the MEMS switch to flow to the auxiliary circuit.

According to another embodiment of the invention, a MEMS relay circuit includes a MEMS switching circuit having a MEMS switch moveable between an open position and a closed position to selectively pass a load current therethrough and a driver circuit configured to provide a drive signal to cause the MEMS switch to move between the open and closed positions. The MEMS relay circuit also includes an auxiliary circuit connected in parallel with the MEMS switching circuit to selectively limit a voltage across the MEMS switch, the auxiliary circuit comprising a first MOSFET and a second MOSFET connected in parallel. The MEMS relay circuit further includes a control circuit operably connected to the MEMS switching circuit and the auxiliary circuit to control switching of the MEMS switch and activation of the first and second MOSFETs in the auxiliary circuit. The auxiliary circuit is selectively operable in a low current mode and a high current mode to selectively allow current flow through the first and second MOSFETs, with the first MOSFET being on and the second MOSFET being off in the low current mode and with the first MOSFET and the second MOSFET being on in the high current mode.

According to yet another embodiment of the invention, a method of controlling a micro-electromechanical system (MEMS) relay circuit that includes a MEMS switching circuit, an auxiliary circuit and a control circuit is provided. The method includes receiving at the control circuit one of an Off signal and an On signal comprising a desired operating condition of the MEMS relay circuit. The method also includes sending a driver control signal from the control circuit to a driver circuit of the MEMS switching circuit responsive to the received Off or On signal, the driver control signal causing the driver circuit to selectively provide a voltage to a MEMS switch of the MEMS switching circuit so as to actuate the MEMS switch between a contacting position or non-contacting position. The method further includes sending an auxiliary circuit control signal from the control circuit to the auxiliary circuit responsive to the received Off or On signal, the auxiliary circuit control signal causing the auxiliary circuit to operate in a low current mode or a high current mode to selectively allow current flow through parallelly connected first and second MOSFETs in the auxiliary circuit.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. A switching system, comprising:

a micro-electromechanical system (MEMS) switching circuit including a MEMS switch and a driver circuit, the MEMS switching circuit connectable to a power circuit to receive a load current therefrom;

an auxiliary circuit coupled in parallel with the MEMS switching circuit; and

a control circuit operably connected to the MEMS switching circuit and the auxiliary circuit to control selective switching of a load current towards the MEMS switching circuit and the auxiliary circuit;

wherein the auxiliary circuit comprises:

first and second connections that connect the auxiliary circuit to the MEMS switching circuit on opposing sides of the MEMS switch;

a first solid state switch;

a second solid state switch connected in parallel with the first solid state switch; and

a resonant circuit connected between the first solid state switch and the second solid state switch;

wherein the first solid state switch, the second solid state switch and the resonant circuit are selectively activated by the control circuit to limit a voltage across the MEMS switch by diverting at least a portion of the load current away from the MEMS switch to flow to the auxiliary circuit prior to the MEMS switch changing state.

2. The switching system of claim **1** wherein the resonant circuit comprises an inductor and a capacitor, the capacitor being pre-charged so as to cause current to flow through the resonant circuit in a direction toward the second solid state switch.

3. The switching system of claim **2** wherein the auxiliary circuit further comprises a pre-charge circuit configured to pre-charge the capacitor.

4. The switching system of claim **1** wherein the control circuit is programmed to:

receive an On-Off signal indicative of a desired operating state of the switching system;

responsive to the received On-Off signal, transmit a control signal to the driver circuit to cause the MEMS switch to actuate to a contacting or non-contacting position within a prescribed switching interval;

activate the auxiliary circuit during the switching interval when the MEMS switch is switching between the contacting and non-contacting positions, such that at least a portion of the load current flows toward the auxiliary circuit; and

deactivate the auxiliary circuit upon reaching the contacting or non-contacting position after completion of the switching interval, such that the load current flows through the MEMS switch in its closed state and such that the MEMS switch sustains a full system voltage in its open state.

5. The switching system of claim **4** wherein the control circuit is programmed to operate the auxiliary circuit in one of a low current mode and a high current mode.

6. The switching system of claim **5** further comprising at least one sensing circuit positioned to sense at least one of a current and a voltage flowing through or across the MEMS switch; and

wherein, in operating the auxiliary circuit in one of the low current mode and the high current mode, the control circuit is programmed to:

receive an input from the at least one sensing circuit regarding the at least one of the sensed current and voltage;

compare the at least one of the sensed current and voltage to a respective current threshold and/or voltage threshold;

operate the auxiliary circuit in the low current mode if the at least one of the sensed current and voltage is below the respective current threshold and/or voltage threshold; and

operate the auxiliary circuit in the high current mode if the at least one of the sensed current and voltage is above the respective current threshold and/or voltage threshold.

7. The switching system of claim **5** wherein, in operating the auxiliary circuit in low current mode, the control circuit is programmed to:

activate the first solid state switch to cause at least a portion of the load current to flow through the first solid state switch;

subsequent to the activation of the first solid state switch, transmit the control signal to the driver circuit to cause the MEMS switch to begin actuating between the contacting and non-contacting positions; and

deactivate the first solid state switch upon the MEMS switch being fully actuated to the contacting or non-contacting position.

8. The switching system of claim **5** wherein, in operating the auxiliary circuit in high current mode, the control circuit is programmed to:

activate the first solid state switch to cause at least a portion of the load current to flow through the first solid state switch;

activate the resonant circuit and the second solid state switch, such that at least a portion of the load current flows through both the first solid state switch and the second solid state switch;

subsequent to the activation of the first and second solid state switches and the resonant circuit, transmit the control signal to the driver circuit to cause the MEMS switch to begin actuating between the contacting and non-contacting positions;

deactivate the second solid state switch upon the MEMS switch being fully actuated to the contacting or non-contacting position; and

deactivate the first solid state switch after resonance in the resonant circuit has stopped.

9. The switching system of claim **1** further comprising:

a third solid state switch positioned in series with the first solid state switch; and

a fourth solid state switch positioned in series with the second solid state switch;

wherein the first, second, third, and fourth solid state switches provide an auxiliary circuit configured to receive AC power from the power circuit.

10. The switching system of claim **1** further comprising an additional MEMS switch connected to the second connection of the auxiliary circuit so as to be positioned in series with the auxiliary circuit, the additional MEMS switch being operable to selectively connect and disconnect the auxiliary circuit from the power circuit so as to provide electrical isolation therebetween.

11. The switching system of claim **1** wherein the first and second solid state switches comprise MOSFETs configured to conduct current therethrough when activated.

12. The switching system of claim **1** wherein the MEMS switch comprises one of a series switch and a shunt switch.

13. A micro-electromechanical system (MEMS) relay circuit comprising:

a MEMS switching circuit including:

a MEMS switch moveable between a non-contacting position and a contacting position to selectively pass a load current therethrough; and

a driver circuit configured to provide a drive signal to cause the MEMS switch to move between the non-contacting and contacting positions;

an auxiliary circuit connected in parallel with the MEMS switching circuit to selectively limit a voltage across the MEMS switch, the auxiliary circuit comprising a first MOSFET and a second MOSFET connected in parallel; and

a control circuit operably connected to the MEMS switching circuit and the auxiliary circuit to control switching of the MEMS switch and activation of the first and second MOSFETs in the auxiliary circuit;

wherein the auxiliary circuit is selectively operable in a low current mode and a high current mode to selectively allow current flow through the first and second MOSFETs, with the first MOSFET being on and the second MOSFET being off in the low current mode and with the first MOSFET and the second MOSFET being on in the high current mode.

14. The MEMS relay circuit of claim **13** wherein the auxiliary circuit further comprises:

a resonant circuit connected between the MOSFET and the second MOSFET, the resonant circuit comprising an inductor and a capacitor; and

a pre-charge circuit configured to selectively pre-charge the capacitor so as to cause current to flow through the resonant circuit in a direction toward the second MOSFET when the resonant circuit is activated.

15. The MEMS relay circuit of claim **14** wherein, in operating the auxiliary circuit in high current mode, the control circuit is programmed to:

turn on the first MOSFET to cause at least a portion of the load current to flow through the first MOSFET;

turn on the second MOSFET and activate the resonant circuit, such that at least a portion of the load current flows through both the first MOSFET and the second MOSFET;

subsequent to turning on the first and second MOSFETs and the resonant circuit, transmit a control signal to the driver circuit to cause the MEMS switch to begin actuating between the non-contacting and contacting positions;

turn off the second MOSFET upon the MEMS switch being fully actuated to the non-contacting or contacting position; and

turn off the first MOSFET after resonance in the resonant circuit has stopped.

16. The MEMS relay circuit of claim **13** wherein, in operating the auxiliary circuit in low current mode, the control circuit is programmed to:

turn on the first MOSFET to cause at least a portion of the load current to flow through the first MOSFET;

subsequent to the turning on the first MOSFET, transmit the control signal to the driver circuit to cause the MEMS switch to begin actuating between the non-contacting and contacting positions; and

turn off the first MOSFET upon the MEMS switch being fully actuated to the non-contacting or contacting position.

17. The MEMS relay circuit of claim **13** further comprising a current sensing circuit positioned to sense a current flowing through the MEMS switch when in the closed position; and

wherein the control circuit is programmed to:

receive an input from the current sensing circuit regarding the current flowing through the MEMS switch;

compare the current flowing through the MEMS switch to a current threshold;

operate the auxiliary circuit in the low current mode if the current flowing through the MEMS switch is below the current threshold; and

operate the auxiliary circuit in the high current mode if the current flowing through the MEMS switch is above the current threshold.

18. The MEMS relay circuit of claim **13** further comprising a voltage sensor positioned to sense a voltage across the MEMS switch when in the open position; and

wherein the control circuit is programmed to:

receive an input from the voltage sensor regarding the voltage across the MEMS switch;

compare the voltage across the MEMS switch to a voltage threshold;

operate the auxiliary circuit in the low current mode if the voltage across the MEMS switch is below the voltage threshold; and

operate the auxiliary circuit in the high current mode if the voltage across the MEMS switch is above the voltage threshold.

19. The MEMS relay circuit of claim **13** wherein the control circuit is programmed to operate the auxiliary circuit in the high current mode as a default mode of operation when the MEMS switch is in the open position.

20. The MEMS relay circuit of claim **13** wherein, in operating the auxiliary circuit in the low current mode or the high current mode, the control circuit is programmed to turn on the first MOSFET or turn on the first and second MOSFETs, respectively, for a duration of a switching interval during which the MEMS switch is moved between the non-contacting position and the contacting position.

21. A method of controlling a micro-electromechanical system (MEMS) relay circuit that includes a MEMS switching circuit, an auxiliary circuit and a control circuit, the method comprising:

receiving at the control circuit one of an Off signal and an On signal comprising a desired operating condition of the MEMS relay circuit;

sending a driver control signal from the control circuit to a driver circuit of the MEMS switching circuit responsive to the received Off or On signal, the driver control signal causing the driver circuit to selectively provide a voltage to a MEMS switch of the MEMS switching circuit so as to actuate the MEMS switch between a contacting position and a non-contacting position; and

sending an auxiliary circuit control signal from the control circuit to the auxiliary circuit responsive to the received Off or On signal, the auxiliary circuit control signal causing the auxiliary circuit to operate in a low current mode or a high current mode to limit a voltage across the MEMS switch by selectively allowing current flow through parallelly connected first and second MOSFETs in the auxiliary circuit prior to the MEMS switch changing state.

22. The method of claim 21 wherein operating the auxiliary circuit in the low current mode further comprises:

operating the first MOSFET of the auxiliary circuit in an On condition to allow a flow of current therethrough;

operating the second MOSFET of the auxiliary circuit in an Off condition to prevent a flow of current therethrough.

23. The method of claim 21 wherein operating the auxiliary circuit in the high current mode further comprises:

operating the first MOSFET of the auxiliary circuit in an On condition to allow a flow of current therethrough;

operating the second MOSFET of the auxiliary circuit in an On condition to allow a flow of current therethrough;

activating a resonant circuit of the auxiliary circuit to direct a flow of current from the first MOSFET to the second MOSFET.

24. The method of claim 21 further comprising:

sensing, via a current sensing circuit, a current flowing through the MEMS switch when in the contacting position;

receiving at the control circuit an input from the current sensing circuit regarding the current flowing through the MEMS switch;

comparing the current flowing through the MEMS switch to a current threshold;

operating the auxiliary circuit in the low current mode if the current flowing through the MEMS switch is below the current threshold; and

operating the auxiliary circuit in the high current mode if the current flowing through the MEMS switch is above the current threshold.

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