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(54) **DC POWER SUPPLY**

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(57) **ABSTRACT**

A DC power supply including a resonant circuit on a secondary side of a transformer suppresses a surge voltage during power recovery of diodes constituting a rectifier circuit, correctly estimates a load current from a secondary current of the transformer, and adjusts supplied power when a load is light. The DC power supply includes a DC voltage source, a converter, a transformer, a rectifier circuit, a resonant circuit composed of a resonant switch and a resonant capacitor, a filter reactor, a filter capacitor, a snubber diode, a snubber capacitor, a load, first and second voltage sensors, a current sensor, and a controller for controlling gate pulses of semiconductor devices constituting a converter and the resonant switch and a signal for adjusting operation timings of A/D converters converting the signals of these sensors.

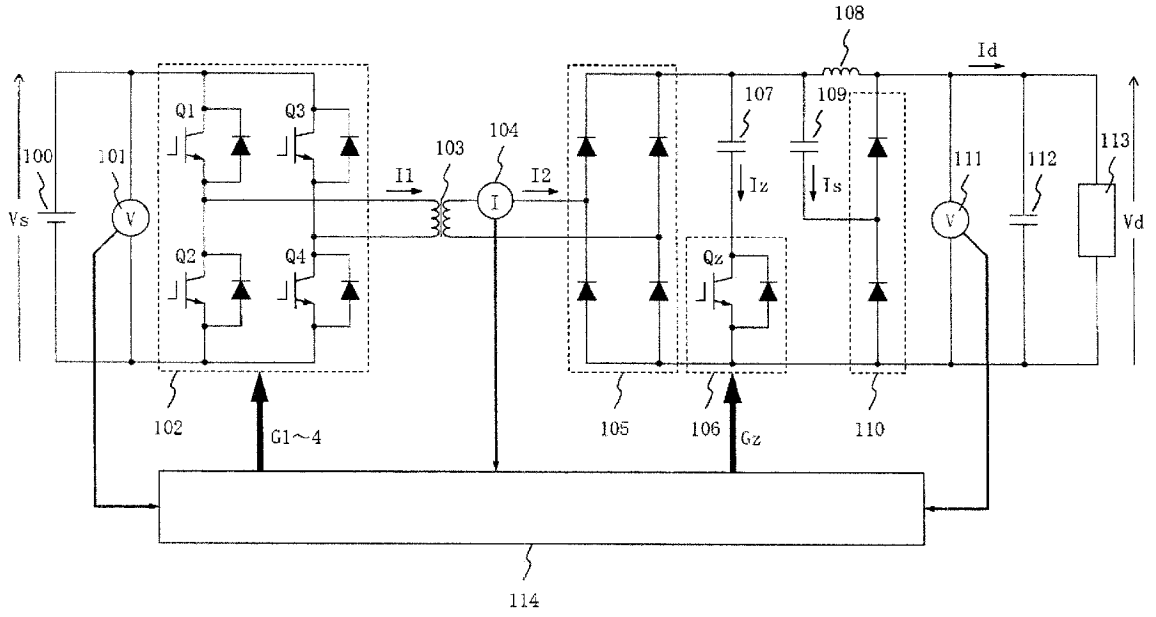


FIG. 1

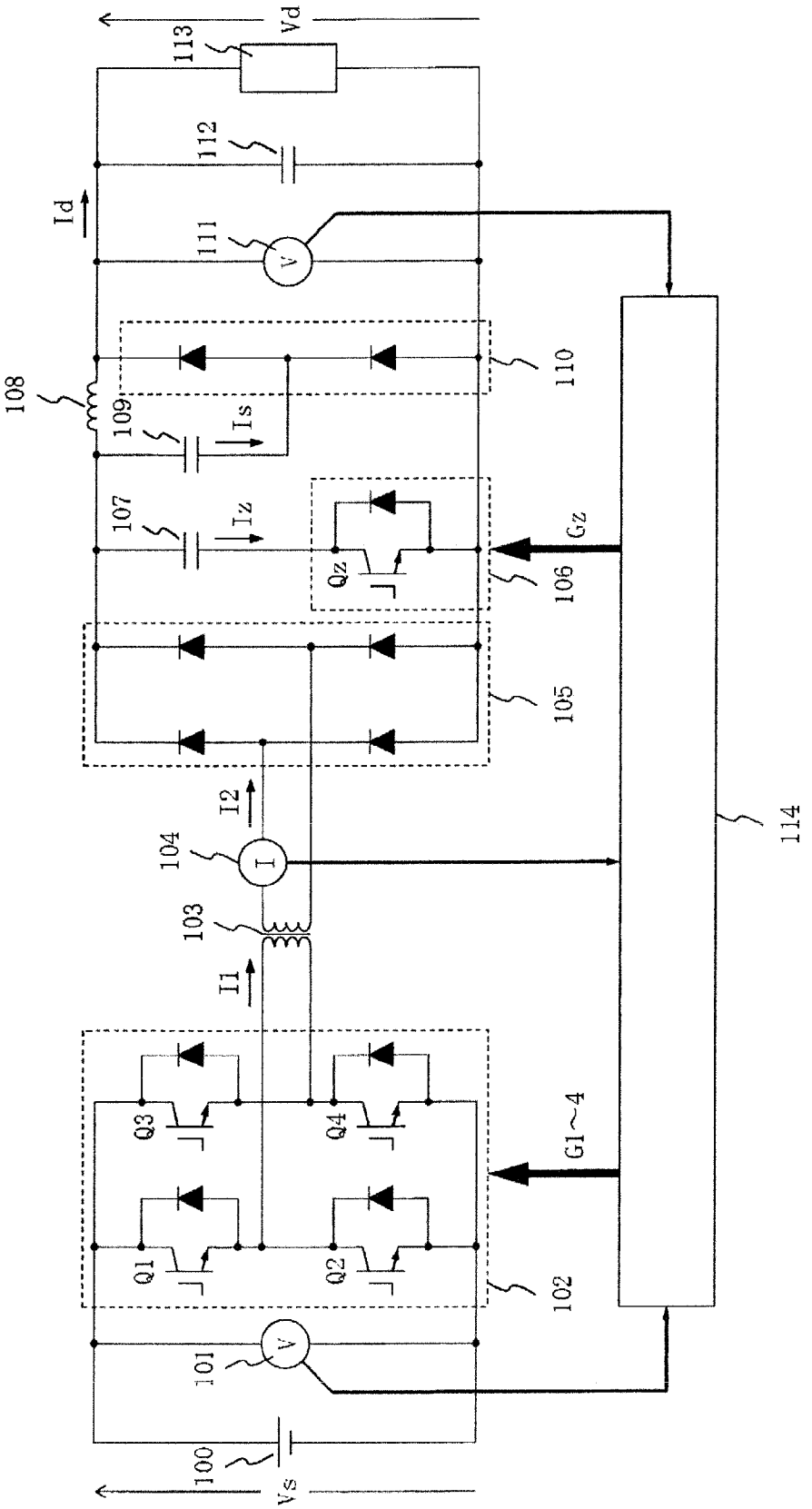

Vd
113
112
Id
111
V
110
108
109
Is
107
Iz
Gz
Qz
106
105
I2
104
I
114
103
I1
Q3
Q4
G1~4
Q1
Q2
102
101
V
100
Vs

FIG. 2

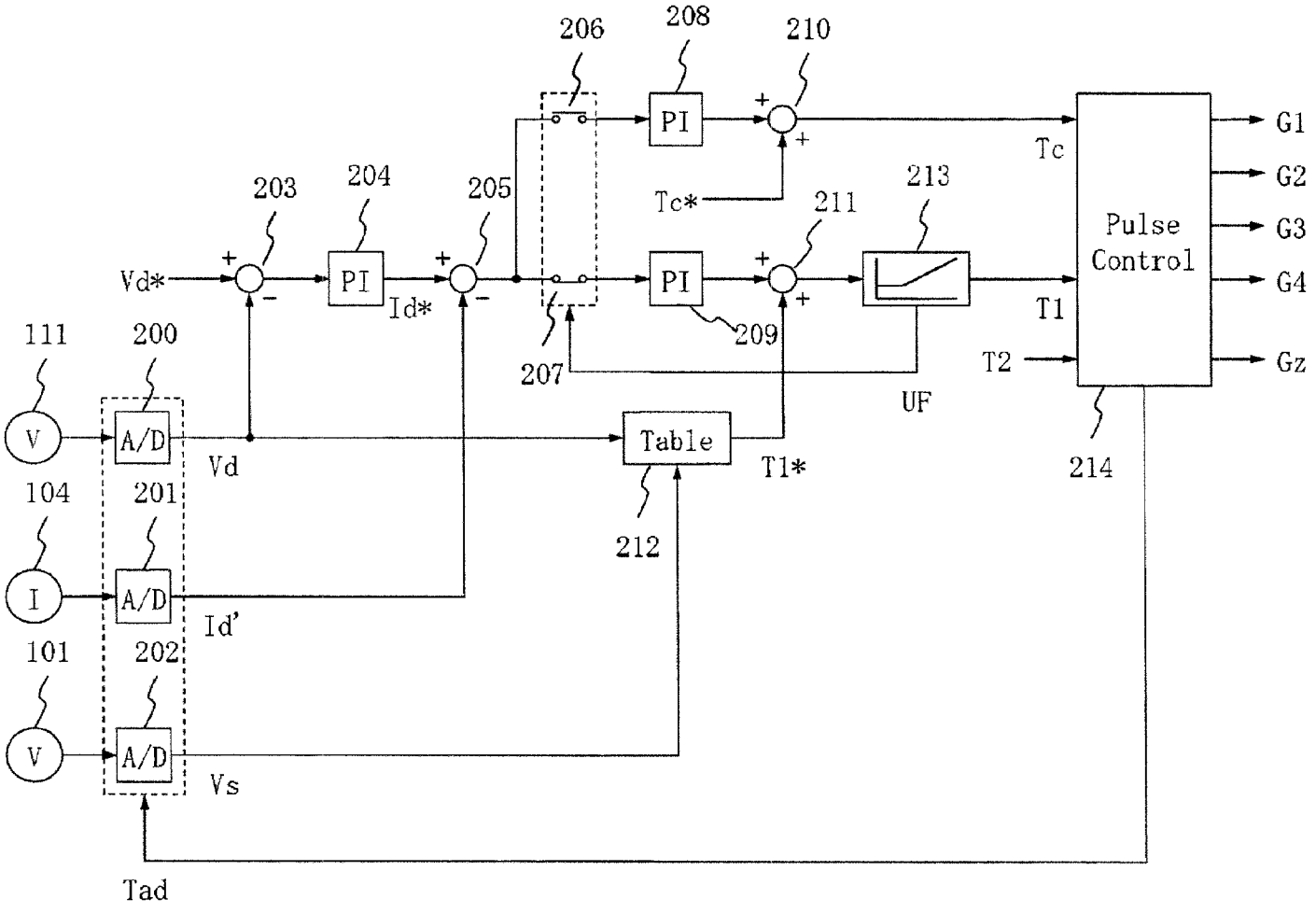

206
208
210
PI
+
+
Tc
Tc*
203
204
205
211
213
Vd*
+
PI
+
PI
+
Pulse
Control
G1
G2
G3
G4
Gz
Id*
209
T1
T2
111
200
207
UF
V
A/D
Vd
Table
T1*
214
104
201
212
I
A/D
Id'
101
202
V
A/D
Vs
Tad

FIG. 3

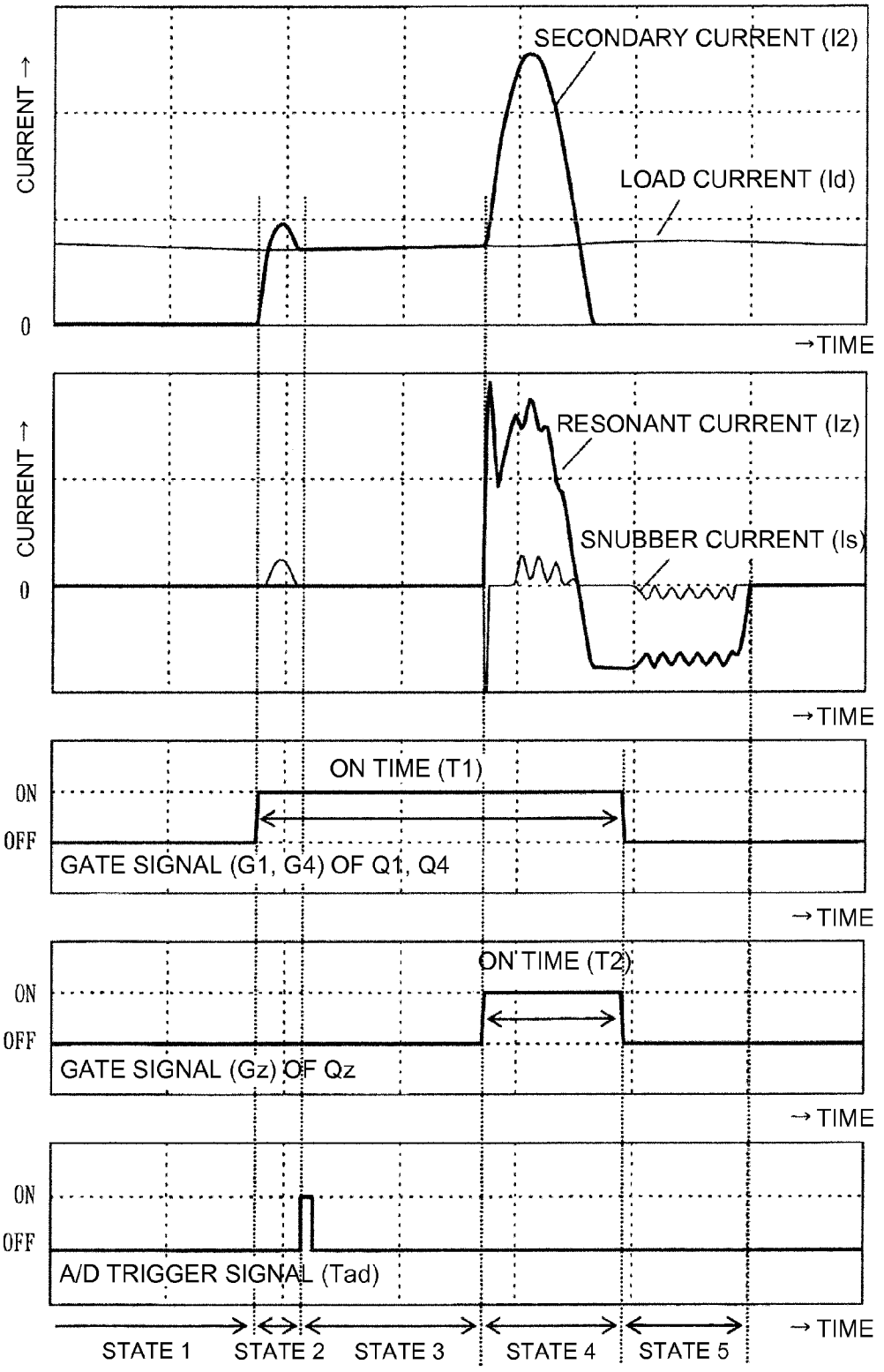

SECONDARY CURRENT (I2)
LOAD CURRENT (Id)
CURRENT →
0
→TIME
RESONANT CURRENT (Iz)
SNUBBER CURRENT (Is)
CURRENT →
0
→TIME
ON TIME (T1)
ON
OFF
GATE SIGNAL (G1, G4) OF Q1, Q4
→TIME
ON TIME (T2)
ON
OFF
GATE SIGNAL (Gz) OF Qz
→TIME
ON
OFF
A/D TRIGGER SIGNAL (Tad)
→TIME
STATE 1
STATE 2
STATE 3
STATE 4
STATE 5

FIG. 4

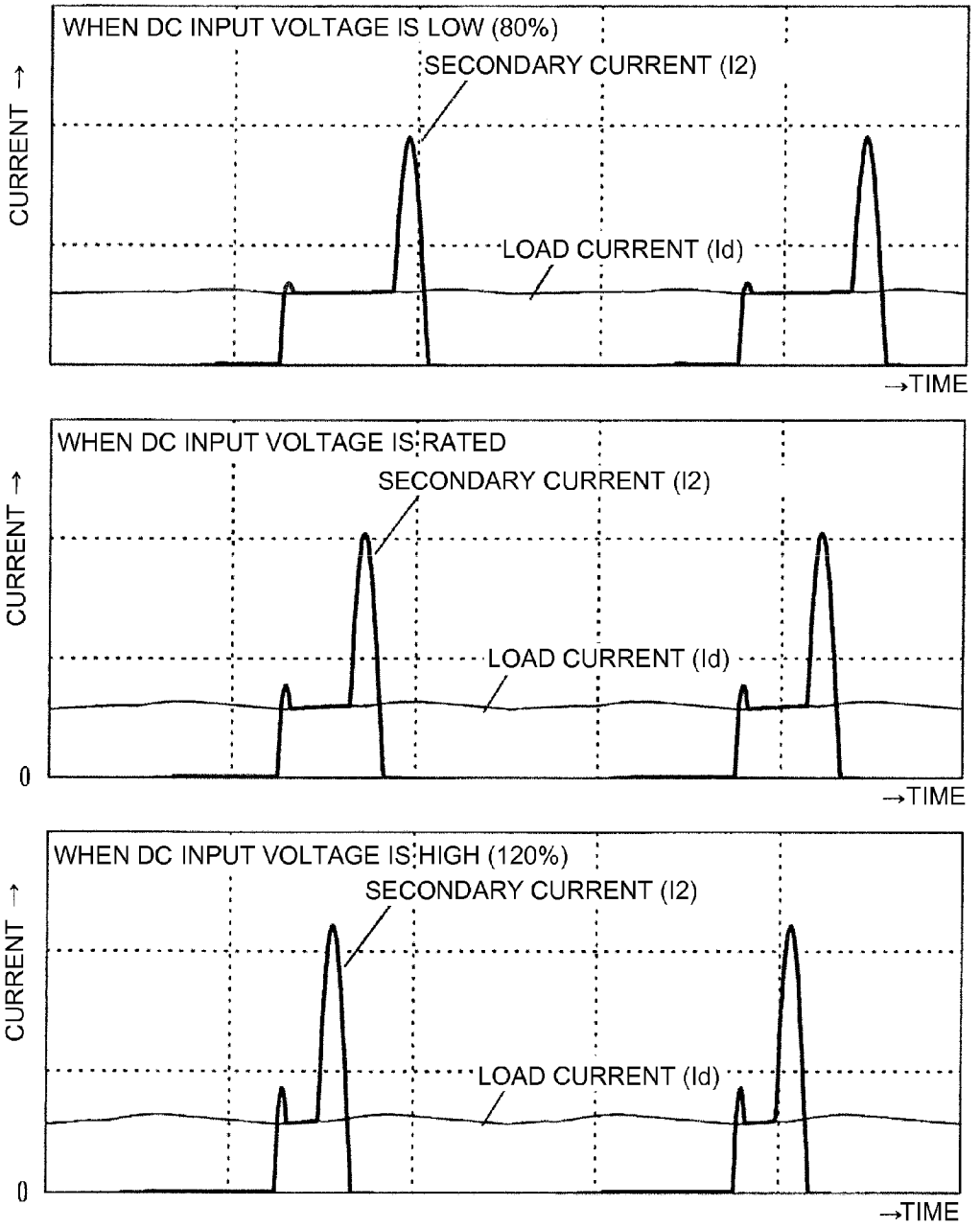

WHEN DC INPUT VOLTAGE IS LOW (80%)
SECONDARY CURRENT (I2)
CURRENT →
LOAD CURRENT (Id)
→TIME
WHEN DC INPUT VOLTAGE IS RATED
SECONDARY CURRENT (I2)
CURRENT →
LOAD CURRENT (Id)
0
→TIME
WHEN DC INPUT VOLTAGE IS HIGH (120%)
SECONDARY CURRENT (I2)
CURRENT →
LOAD CURRENT (Id)
0
→TIME

FIG. 5

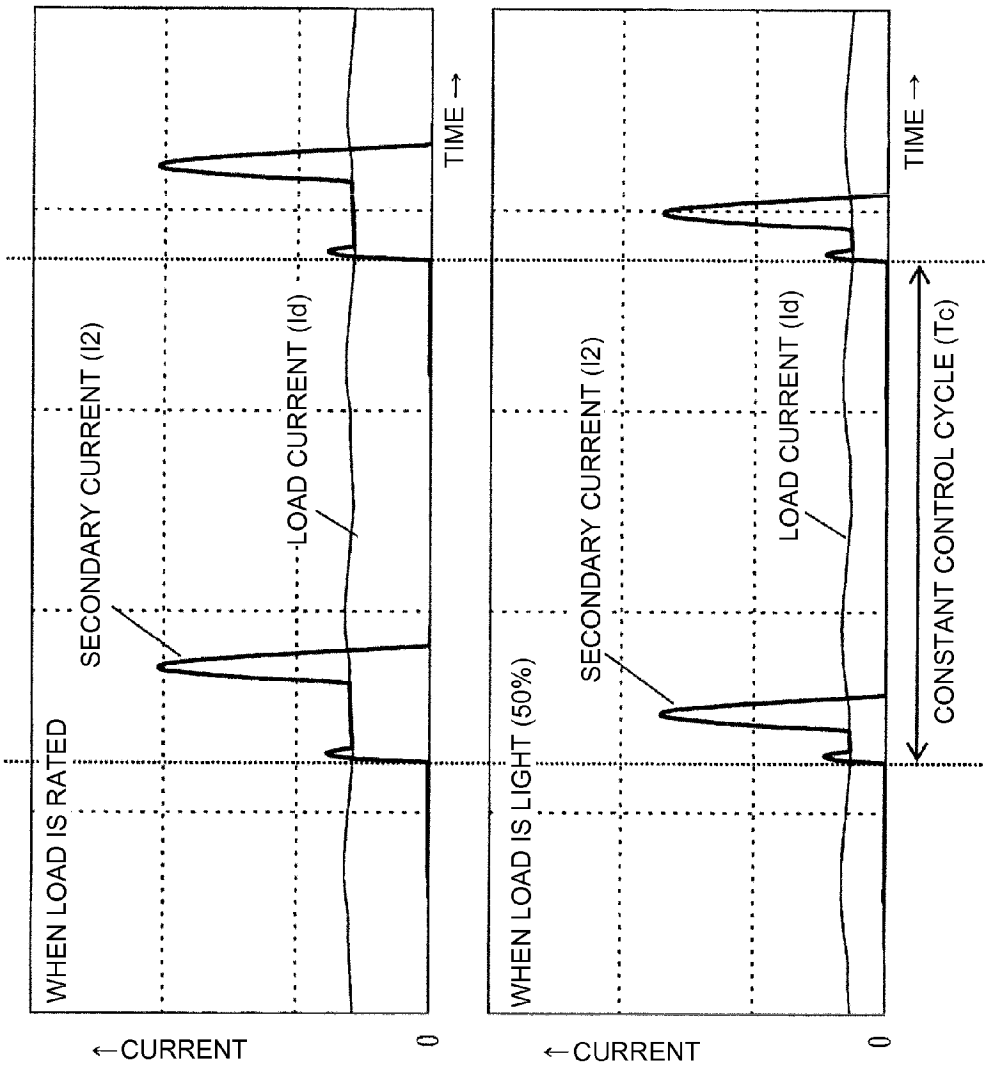

WHEN LOAD IS RATED
SECONDARY CURRENT (I2)
LOAD CURRENT (Id)
TIME →
←CURRENT
0
WHEN LOAD IS LIGHT (50%)
SECONDARY CURRENT (I2)
LOAD CURRENT (Id)
TIME →
CONSTANT CONTROL CYCLE (Tc)
←CURRENT
0

FIG. 6

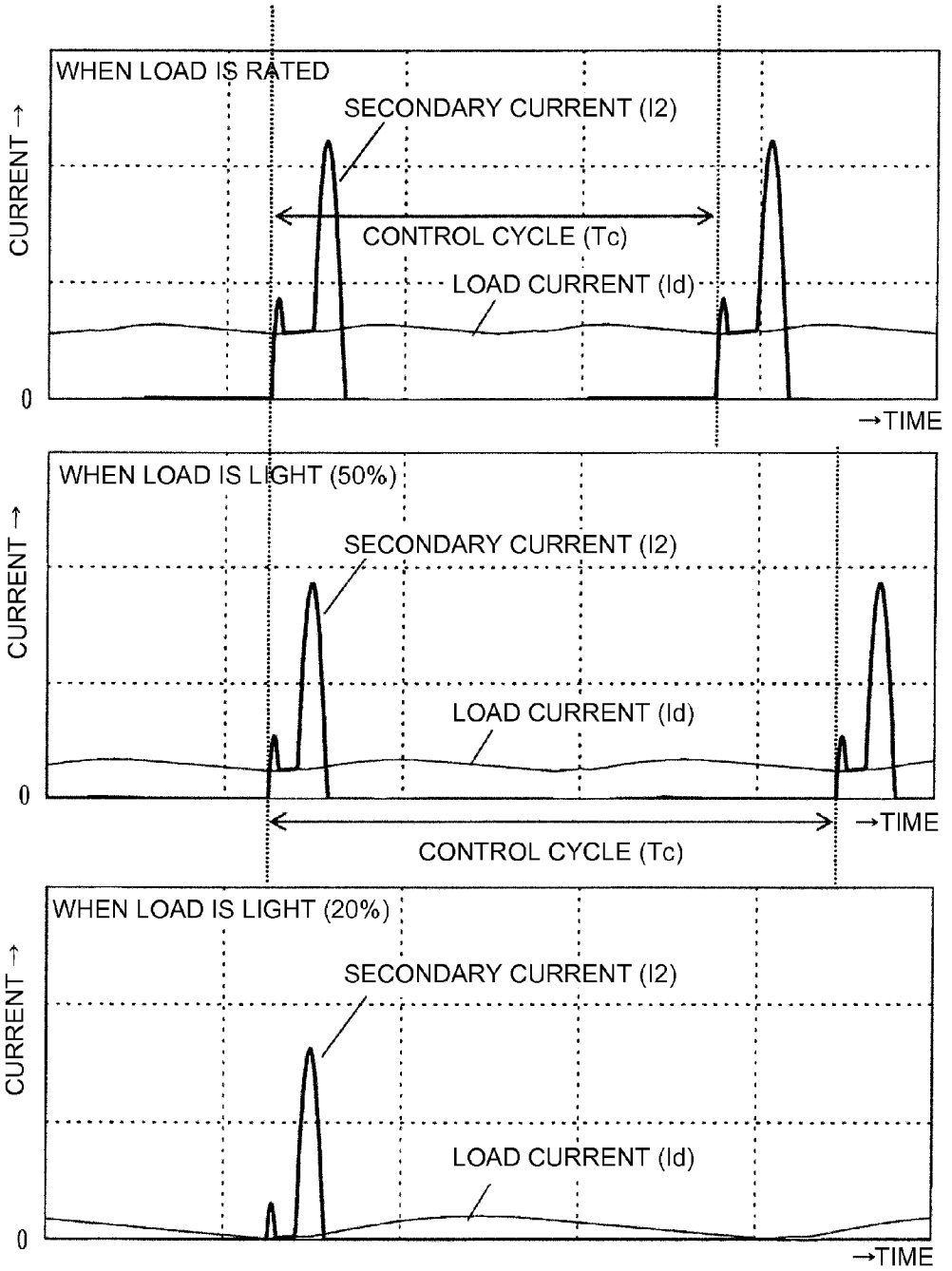

WHEN LOAD IS RATED
SECONDARY CURRENT (I2)
CONTROL CYCLE (Tc)
LOAD CURRENT (Id)
CURRENT →
0
→TIME
WHEN LOAD IS LIGHT (50%)
SECONDARY CURRENT (I2)
LOAD CURRENT (Id)
CURRENT →
0
→TIME
CONTROL CYCLE (Tc)
WHEN LOAD IS LIGHT (20%)
SECONDARY CURRENT (I2)
LOAD CURRENT (Id)
CURRENT →
0
→TIME

FIG. 7

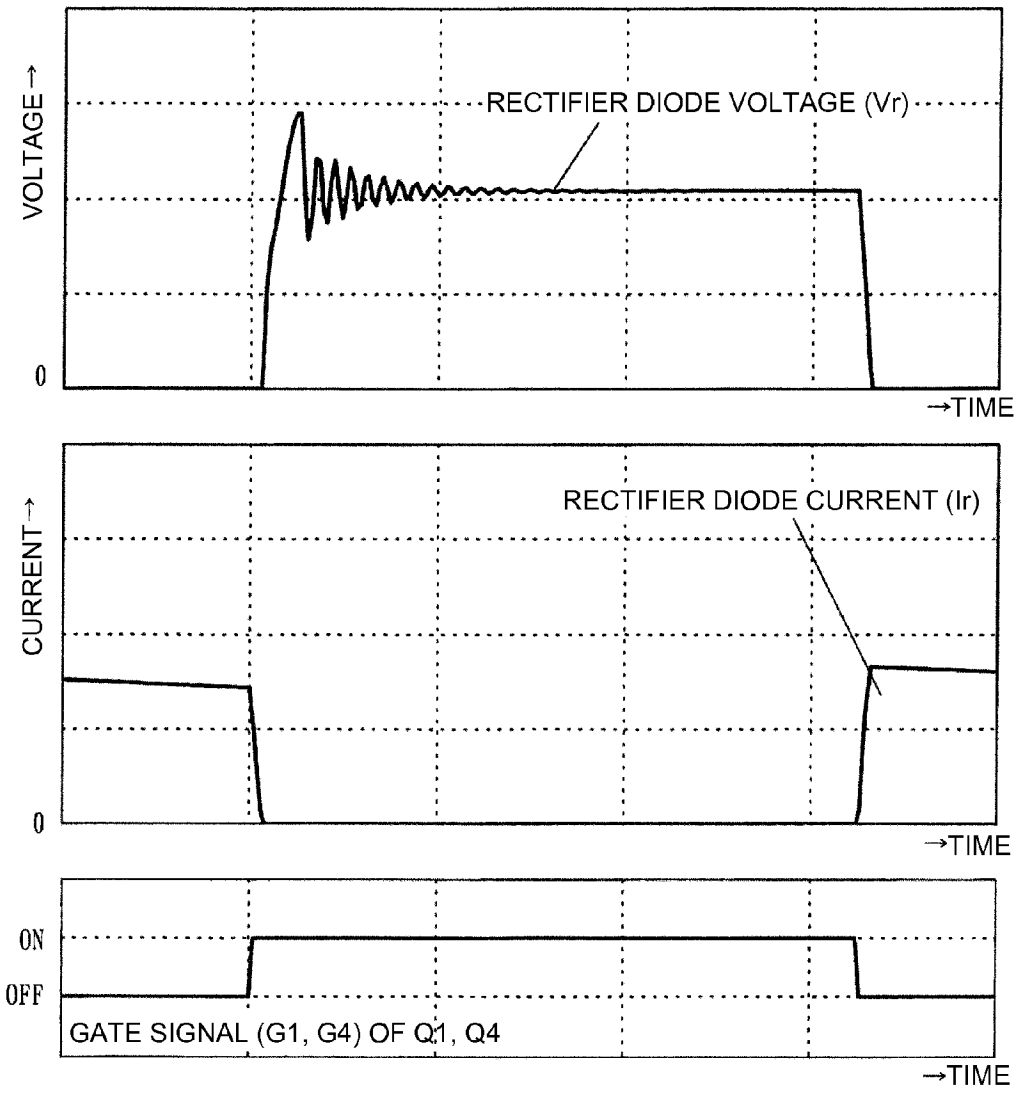

VOLTAGE →
RECTIFIER DIODE VOLTAGE (Vr)
0
→TIME
CURRENT →
RECTIFIER DIODE CURRENT (Ir)
0
→TIME
ON
OFF
GATE SIGNAL (G1, G4) OF Q1, Q4
→TIME

FIG. 8

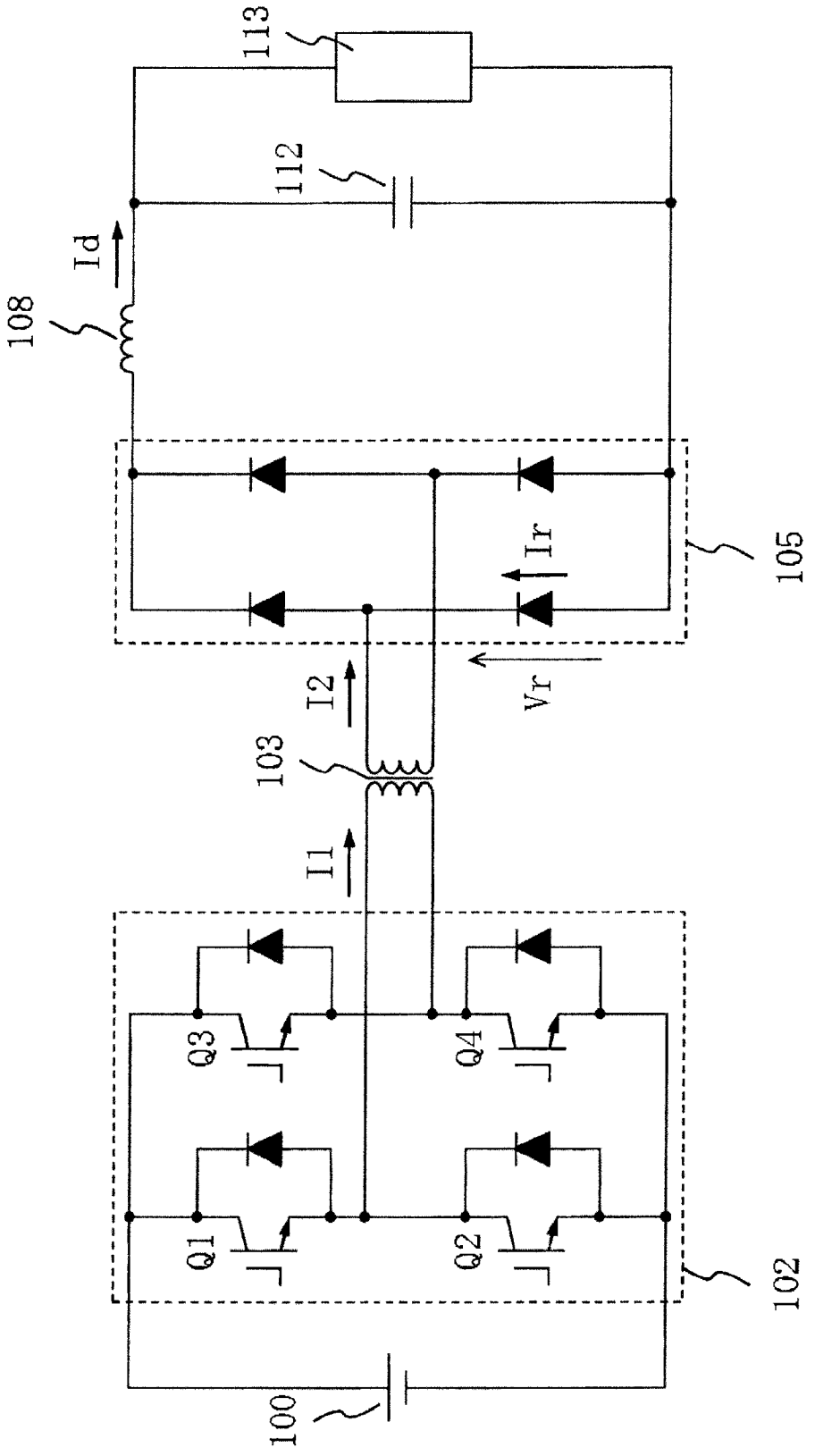


FIG. 9

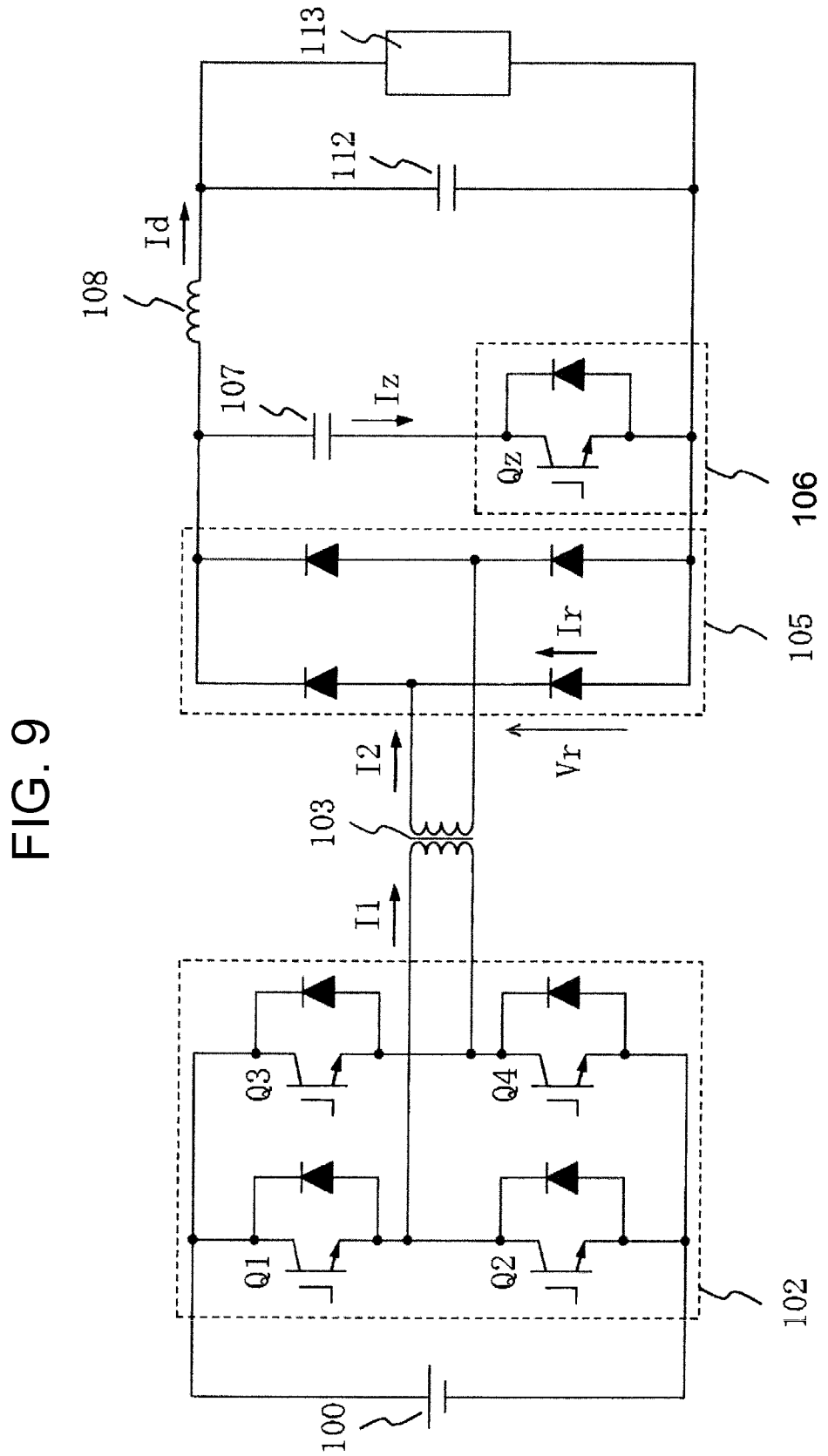
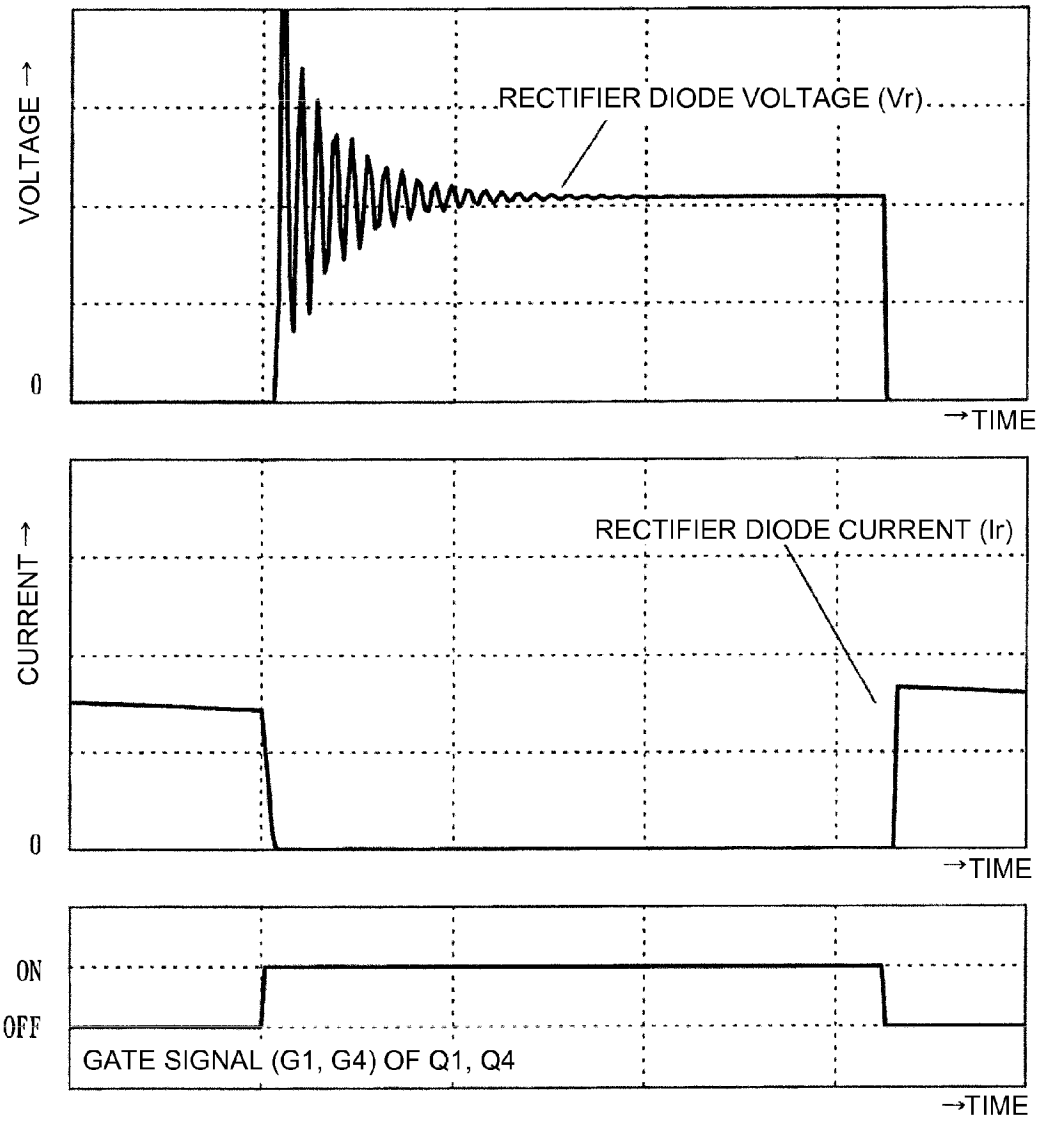


FIG. 10


VOLTAGE →
RECTIFIER DIODE VOLTAGE (Vr)
0
→TIME
CURRENT →
RECTIFIER DIODE CURRENT (Ir)
0
→TIME
ON
OFF
GATE SIGNAL (G1, G4) OF Q1, Q4
→TIME

DC POWER SUPPLY

[0001] The present application is based on and claims priority of Japanese patent application No. 2011-116758 filed on May 25, 2011, the entire contents of which are hereby incorporated by reference.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to a DC power supply using semiconductor devices. More specifically, the present invention relates to a soft-switching DC power supply including a resonant circuit for reducing switching losses in semiconductor devices.

[0004] 2. Description of the Related Art

[0005] A power supply for converting direct current to direct current (hereinafter referred to as a DC power supply) is used to stabilize unstable direct current voltage, change direct current voltage, or provide electric isolation between input and output. Especially, in a DC power supply for providing electric isolation between input and output, a method of downsizing an isolation transformer by increasing an applied frequency is known.

[0006] FIG. **8** shows a circuit configuration disclosed in Japanese Patent Laid-Open Publication No. 2010-178501 (Patent Document 1) as an example. A DC power supply shown in FIG. **8** includes: a DC voltage source **100**; a converter **102** for converting DC power outputted from the DC voltage source **100** into AC power; a transformer **103** for inputting the AC power outputted from the converter **102**; a rectifier circuit **105** for converting the AC power outputted from the transformer **103** into DC power; a filter reactor **108** and filter capacitor **112** for smoothing the DC power outputted from the rectifier circuit **105**; and a load **113** connected in parallel to the filter capacitor **112**.

[0007] In the DC power supply shown in FIG. **8**, switching losses in semiconductor devices composing the converter **102** are increased in accordance with an applied frequency. Accordingly, a technique (soft-switching) for reducing switching losses using a resonant circuit is suggested. FIG. **9** shows a circuit configuration disclosed in Japanese Patent Laid-Open Publication No. 4-368464 (Patent Document 2) and O. Deblecker, A. Moretti, and F. Vallee: "Comparative Analysis of Two zero-Current Switching Isolated DC-DC Converters for Auxiliary Railway Supply" SPEEDAM2008 (Non-Patent Document 1) as an example.

[0008] A DC power supply shown in FIG. **9** includes: a DC voltage source **100**; a converter **102** for converting DC power outputted from the DC voltage source **100** into AC power; a transformer **103** for inputting the AC power outputted from the converter **102**; a rectifier circuit **105** for converting the AC power outputted from the transformer **103** into DC power; a resonant circuit which is composed of a resonant switch **106** and a resonant capacitor **107** and which is connected in parallel to a DC output side of the rectifier circuit **105**; a filter reactor **108** and filter capacitor **112** for smoothing the DC power outputted from the rectifier circuit **105**; and a load **113** connected in parallel to the filter capacitor **112**.

[0009] The DC power supply shown in FIG. **9** activates the resonant switch **106** at the timing of turning off the converter **102** to superpose a resonant current Iz on a secondary current I**2**. Accordingly, the secondary current I**2** can be temporarily reduced to zero and a primary current I**1** can be temporarily reduced to a level of only excitation current. By turning off the converter **102** at this timing, the turn-off power loss of the converter **102** can be considerably reduced.

[0010] In the DC power supply shown in FIG. **8**, while semiconductor devices Q**1** to Q**4** constituting the converter **102** are off, the primary current I**1** and the secondary current I**2** are zero but a free wheeling current continues to flow through diodes constituting the rectifier circuit **105**. When the semiconductor devices Q**1** and Q**4** constituting the converter **102** are turned on, the primary current I**1** and the secondary current I**2** start to flow and the magnitude of the secondary current I**2** matches that of a load current Id. At this time, a current having the same magnitude as that of the secondary current I**2** flows through a half of the diodes constituting the rectifier circuit **105** and no current flows through the other half of the diodes.

[0011] A voltage waveform and a current waveform of the latter diodes are shown in FIG. **10**. When a state where a current flows through the diodes is shifted to a state where the current is interrupted and a voltage is applied, carriers stored in the diodes are discharged and a current (reverse recovery current) temporarily flows in a reverse direction. Then, a serge voltage is generated. The surge voltage continues to oscillate for a while due to resonance caused by junction capacitance of the diodes and circuit inductance. A recovery phenomenon depends on characteristics of diodes. When the surge voltage is intensely generated as shown in FIG. **10**, the surge voltage may exceed a device withstanding voltage and the devices may be destroyed. Even when the surge voltage does not exceed the device withstanding pressure, an electromagnetic noise of a high frequency may be generated, and accordingly, other electronic devices may be negatively affected. For example, they may be electromagnetically interfered.

[0012] As a countermeasure against a surge voltage during power recovery, a technique of providing a CR circuit (snubber circuit) in parallel to diodes constituting a rectifier circuit is known. As conventional examples of the countermeasure against the surge voltage, a DC-DC converter disclosed in Japanese Patent Laid-Open Publication No. 2006-352959 (Patent Document 3), a device for transmitting electric power disclosed in Japanese Patent Laid-Open Publication No. 2009-273355 (Patent Document 4), and a low-loss converter disclosed in Japanese Patent Laid-Open Publication No. 2008-79403 (Patent Document 5) are known.

[0013] The circuit shown in FIG. **9** as a conventional example has three problems. The first problem is how to reduce the surge voltage of the diodes constituting the rectifier circuit **105** during the power recovery.

[0014] The second problem is that it is difficult to recognize a correct load state from the secondary current I**2** because the resonant current Iz, which flows through the resonant circuit composed of the resonant capacitor **107** and resonant switch **106** added to reduce the turn-off loss of the converter **102**, is superposed on the secondary current I**2**. A current sensor for directly detecting the load current Id may be provided to recognize the correct load state. The problem here is, however, how to correctly estimate the load current Id from the secondary current I**2** for saving the cost and recognize the correct load state without the current sensor for detecting the load current Id.

[0015] The third problem is how to perform the smooth control when the load is light. Since the amplitude of the resonant current Iz flowing through the resonant capacitor

107 is proportional to a DC input voltage Vs, an energy supplied by the resonant current Iz is proportional to the square of the DC input voltage Vs. When the DC input voltage Vs is high, a considerably high energy is supplied only by the resonant current Iz. Thus, it is difficult to reduce the supplied electric power.

SUMMARY OF THE INVENTION

[0016] To solve the first problem, the DC power supply according to an aspect of the present invention including a DC voltage source, a converter for converting DC power outputted from the DC voltage source to AC power, a transformer for receiving the AC power outputted from the converter, a rectifier circuit for converting the AC power outputted from the transformer to DC power, a resonant circuit composed of a resonant switch and a resonant capacitor connected in parallel to a DC output side of the rectifier circuit; a filter reactor and filter capacitor for smoothing the DC power outputted from the rectifier circuit, and a load connected in parallel to the filter capacitor, includes: a snubber circuit connected in parallel to the filter capacitor. To solve the second and third problems, the DC power supply according to the aspect of the present invention further includes: a first voltage sensor for detecting a DC voltage outputted from the DC voltage source; a current sensor for detecting a secondary current of the transformer; a second voltage sensor for detecting a voltage of the filter capacitor; and a controller for adjusting gate pulses of the converter and the resonant switch and detection timings of the first and second voltage sensors and the current sensor.

[0017] In the DC power supply according to the aspect of the present invention, the controller includes: first controlling means for inputting output signals of the first and second voltage sensors and the current sensor and adjusting supplied power by adjusting a gate pulse width in accordance with a sensor input while an operating frequency of the converter is maintained constant; and second controlling means for adjusting the supplied power by adjusting the operating frequency of the converter in accordance with the sensor input while the gate pulse width of the converter is maintained constant.

[0018] In the power supply according to the aspect of the present invention, the snubber circuit is composed of a diode bridge (snubber diode) and a capacitor (snubber capacitor) for connecting an output of the diode bridge to a DC output side of the rectifier circuit, and the controller includes means for inputting the output signal of the current sensor and performing sampling and holding in synchronization with the operating frequency of the converter during a period except for ¾ of a resonant cycle obtained by an electrostatic capacitance of the resonant capacitor and a circuit inductance during turn-on of the converter and ½ of a resonant cycle obtained by an electrostatic capacitance of the snubber capacitor and the circuit inductance.

[0019] According to the present invention, due to the snubber circuit composed of the snubber diode serving as the diode bridge connected in parallel to the filter capacitor and the snubber capacitor for connecting an output at an intermediate point of the diode bridge of the snubber diode serving as the diode bridge to the DC output side of the diodes of the rectifier circuit, the surge voltage generated during power recovery of the diodes of the rectifier circuit can be reduced and thus the electromagnetic noise can be also reduced.

[0020] Since the current sensor for the secondary current of the transformer is provided and sampling and holding are performed by inputting an output signal from the current sensor in synchronization with the operating frequency of the converter after ½ of the resonant cycle obtained by the electrostatic capacitance of the snubber capacitor and the circuit inductance from turn-on of the converter and before ¾ of the resonant cycle obtained from the electrostatic capacitance of the resonant capacitor and the circuit inductance from turn-off, the load current can be correctly estimated from the secondary current.

[0021] Since the first controlling means for adjusting the supplied power by adjusting the gate pulse width in accordance with the sensor input while the operating frequency of the converter is maintained constant and the second controlling means for adjusting the supplied power by adjusting the operating frequency of the converter in accordance with the sensor input while the gate pulse width of the converter is maintained constant are provided, the supplied power can be reduced when the load is light.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] FIG. **1** shows a circuit configuration of a DC power supply according to the present invention;

[0023] FIG. **2** shows an internal arrangement of a controller of the DC power supply according to the present invention;

[0024] FIG. **3** shows details of a control timing as an example of an operation waveform according to the present invention;

[0025] FIG. **4** shows adjustments in accordance with a DC input voltage as the example of the operation waveform according to the present invention;

[0026] FIG. **5** shows adjustments in accordance with a load factor as the example of the operation waveform according to the present invention;

[0027] FIG. **6** shows adjustments in accordance with the load factor as the example of the operation waveform according to the present invention;

[0028] FIG. **7** shows a voltage waveform and a current waveform of a rectifier diode according to the present invention;

[0029] FIG. **8** shows a circuit configuration of a DC power supply according to a conventional technique (Patent Document 1);

[0030] FIG. **9** shows a circuit configuration of a DC power supply according to another conventional technique (Patent Document 2 and the like); and

[0031] FIG. **10** shows a voltage waveform and a current waveform of a rectifier diode in the DC power supply according to the conventional technique (Patent Document 1).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0032] Embodiments of the present invention will be explained below with reference to the accompanying drawings.

First Embodiment

[0033] FIG. **1** shows an embodiment of the present invention. A DC power supply shown in FIG. **1** includes: a DC voltage source **100**; a first voltage sensor **101** for detecting a DC input voltage Vs as an output voltage of the DC voltage source **100**; a converter **102** for converting DC power output-

ted from the DC voltage source **100** into AC power; a transformer **103** for inputting the AC power outputted from the converter **102**; a current sensor **104** for detecting a secondary current I2 of the transformer **103**; a rectifier circuit **105** for converting the AC power outputted from the transformer **103** into DC power; a resonant circuit which is composed of a resonant switch **106** and a resonant capacitor **107** and connected in parallel to a DC output side of the rectifier circuit **105**; a filter reactor **108** and filter capacitor **112** for smoothing the DC power outputted from the rectifier circuit **105**; a snubber diode **110** serving as a diode bridge connected in parallel to the filter capacitor **112**; a snubber capacitor **109** for connecting the output at the intermediate point of the diode bridge of the snubber diode **110** to the DC output side of the rectifier circuit **105**; a second voltage sensor **111** for detecting a DC output voltage Vd of the filter capacitor **112**; a load **113** connected in parallel to the filter capacitor **112**; and a controller **114** for inputting the DC input voltage Vs detected by the first voltage sensor **101**, the DC output voltage Vd detected by the second voltage sensor **111**, and the secondary current I2 detected by the current sensor **104**, and controlling gate signals G1 to G4 of semiconductor devices Q1 to Q4 constituting the converter **102** and a gate signal Gz of a semiconductor device Qz constituting the resonant switch **106**.

[0034] FIG. **2** shows the detail arrangement of the controller **114**. The controller **114** of the DC power supply shown in FIG. **2** includes: a first A/D converter **200** for inputting an output signal of the second voltage sensor **111**; a second A/D converter **201** for inputting an output signal of the current sensor **104**; a third A/D converter **202** for inputting an output signal of the first voltage sensor **101**; a first subtractor **203** for obtaining a deviation between a DC output voltage command Vd* and a DC output voltage Vd as an output signal of the first A/D converter **200**; a first PI controller **204** for inputting an output signal of the first subtractor **203** and outputting a load current command Id*; a second subtractor **205** for obtaining a deviation between the load current command Id* outputted from the first PI controller **204** and a load current estimated value Id' as an output signal of the second A/D converter **201**; a second PI controller **208** for inputting an output signal of the second subtractor **205** via an A contact switch **206**; a first adder **210** for obtaining a converter control cycle Tc by adding an output signal of the second PI controller **208** and an initial value Tc* of the converter control cycle; a function table **212** for inputting the DC output voltage Vd as the output signal of the first A/D converter **200** and a DC input voltage Vs as an output signal of the third A/D converter **202** and outputting a turn-on time command T1* of a semiconductor device constituting the converter **102**; a third PI controller **209** for inputting an output signal of the second subtractor **205** via a B contact switch **207**; a second adder **211** for obtaining the sum of the output signal of the third PI controller **209** and the turn-on time command T1* of the semiconductor devices constituting the converter **102** of the function table **212**; a limiter **213** for inputting an output signal of the second adder **211**, limiting a turn-on time T1 of the semiconductor devices constituting the converter **102** within a predetermined range, and outputting an underfloor flag UF determining whether an output is limited or not; and a pulse controller **214** for inputting the control cycle Tc of the converter **102** outputted from the first adder **210**, the turn-on time T1 of the semiconductor devices constituting the converter **102** outputted from the limiter **213**, and a turn-on time T2 of the semiconductor device constituting the resonant switch **106**, and outputting gate signals G1 to G4 of semiconductor devices Q1 to Q4 constituting the converter **102**, a gate signal Gz of a semiconductor device Qz constituting the resonant switch **106**, and a trigger signal Tad of an A/D converter that samples and holds the first to third A/D converters **200** to **202**.

[0035] In accordance with the underflow flag UF outputted from the limiter **213**, the A contact switch **206** and the B contact switch **207** exclusively operate as follows.

a) When the output of the limiter **213** is within a predetermined range (T1>T1min),

[0036] underflow flag UF: off

[0037] A contact switch **206**: opened

[0038] first PI controller **208**: reset, zero output

[0039] first adder **210**: output Tc* (fixed)

[0040] B contact switch **207**: connected

[0041] second PI controller **209**: operating

[0042] limiter **213**: output T1 (variable)

b) When the output of the limiter **213** is limited to a lower limit value (T1=T1min),

[0043] underflow flag UF: on

[0044] A contact switch **206**: connected

[0045] first PI controller **208**: operating

[0046] first adder **210**: output Tc (variable)

[0047] B contact switch **207**: opened

[0048] second PI controller **209**: reset, zero output

[0049] limiter **213**: output Tlmin (fixed)

[0050] FIG. **3** shows an operation waveform of the DC power supply according to the present invention. In FIG. **3**, the following signals are shown from the top.

(1) the secondary current I2 and the load current Id

(2) the resonant current Iz and the snubber current Is

(3) the gate signals G1 and G4 of the semiconductor devices Q1 and Q4 constituting the converter **102**

(4) the gate signal Gz of the semiconductor device Qz constituting the resonant switch **106**

(5) the trigger signal Tad of the first to third A/D converters **200** to **202**

[0051] The horizontal axis of FIG. **3** is a time axis. The state transitions from [state **1**] to [state **5**] with the passage of time.

[0052] [state **1**] When the semiconductor devices Q1 and Q4 constituting the converter **102** are off, the secondary current I2 of the transformer **103** is zero and the load current Id continue to flow through the rectifier circuit **105**.

[0053] [state **2**] When the semiconductor devices Q1 and Q4 constituting the converter **102** are turned on, the secondary current I2 of the transformer **103** starts to flow, and simultaneously, the charge current Is of the snubber capacitor **109** starts to flow. Such a state is continued for approximately half of a resonant cycle obtained by the electrostatic capacitance of the snubber capacitor **109** and the circuit inductance.

[0054] [state **3**] When the charging of the snubber capacitor **109** is finished, the magnitude of the secondary current I2 of the transformer **103** matches that of the load current Id. At the initial timing of such a state, the trigger signal Tad of the A/D converter for operating the first to third A/D converters is outputted and the A/D conversion (sampling and holding) is performed. Accordingly, the value of the load current Id can be obtained using the detected value of the secondary current I2 of the transformer **103**.

[0055] [State **4**] Before the semiconductor devices Q1 and Q4 constituting the converter **102** are turned off, the semiconductor device Qz constituting the resonant switch **106** is turned on at the timing prior to ¾ of the resonant cycle

obtained by the electrostatic capacitance of the resonant capacitor **107** and the circuit inductance. The electric charge charged in the snubber capacitor **109** is instantly discharged and is charged in the resonant capacitor **107**, and subsequently, the snubber capacitor **109** is recharged. The sum of the current value of the resonant current Iz and the current value of the snubber current Is is superposed on the current value of the secondary current I2 of the transformer **103**, and thus the current value of the secondary current I2 of the transformer **103** is increased once. After ½ of the resonant cycle of the resonant capacitor **107**, however, the current value of the secondary current I2 is decreased to zero. The secondary current I2 of the transformer **103** does not flow in the negative direction due to the diodes constituting the rectifier circuit **105**, and accordingly, the current value of the secondary current I2 continues to zero. When the resonant switch **106** is turned off while the current value of the secondary current I2 of the transformer **103** is zero, the turn-off loss of the resonant switch **106** becomes zero because the resonant current Iz flowing through the resonant switch **106** is negative. When the converter **102** is turned off while the current value of the secondary current I2 of the transformer **103** is zero, the turn-off loss of the semiconductor devices Q1 to Q4 constituting the converter **102** can be considerably reduced because the primary current I1 of the transformer **103** is composed of only excitation current.

[0056] [State **5**] When the semiconductor devices Q1 and Q4 constituting the converter **102** are off and the semiconductor device Qz constituting the resonant switch **106** is off, the secondary current I2 of the transformer **103** is zero, but the resonant current Iz continues to flow until the electric charge charged to the resonant capacitor **107** becomes zero. The sum of the resonant current Iz and the snubber current Is is supplied to the load **113** as the load current Id. When the resonant current Iz becomes zero, the state is retuned back to the state **1**.

[0057] FIGS. **7** and **10** show an operation waveform of the DC power supply during power recovery according to the present invention. In FIGS. **7** and **10**, the following signals are shown from the top.

(1) the DC output voltage Vd as a terminal voltage of the diodes constituting the rectifier circuit **105**

(2) the load current Id as a current flowing through the diodes constituting the rectifier circuit **105**

(3) the gate signals G1 and G4 of the semiconductor devices Q1 and Q4 constituting the converter **102**

[0058] While the semiconductor devices Q1 and Q4 constituting the converter **102** are off, the primary current I1 and the secondary current I2 of the transformer **103** are zero but the free wheeling current continues to flow through the diodes constituting the rectifier circuit **105**. When the semiconductor devices Q1 and Q4 are turned on from that state, the primary current I1 and the secondary current I2 of the transformer **103** start to flow and the magnitude of the secondary current I2 of the transformer **103** becomes the same as that of the load current Id. At this time, a current having the same magnitude as that of the secondary current I2 of the transformer **103** flows through a half of the diodes constituting the rectifier circuit **105** and no current flows through the other half of the diodes. A voltage waveform and a current waveform of the latter diodes are shown in FIGS. **7** and **10**.

[0059] When a state where the current flows through the diodes constituting the rectifier circuit **105** transitions to a state where the current is interrupted and a voltage is applied, carriers stored in the diodes constituting the rectifier circuit **105** are discharged and a current (reverse recovery current) flows temporarily in a reverse direction. Then, a serge voltage is generated. As compared to the conventional techniques shown in FIGS. **9** and **10**, it is found that the surge voltage can be reduced by the snubber circuit composed of the snubber capacitor **109** and the snubber diode **110**.

[0060] FIG. **4** shows an example of the operation waveform of the DC power supply according to the present invention. FIG. **4** shows a waveform in a mode where the second PI controller **209** shown in FIG. **2** is operating. In FIG. **4**, the following signals are shown from the top.

(1) the secondary current I2 and the load current Id of the transformer **103** when the DC input voltage Vs is a low voltage (80%) when a load is rated

(2) the secondary current I2 and the load current Id of the transformer **103** when the DC input voltage Vs is a rated voltage when the load is rated

(3) the secondary current I2 and the load current Id of the transformer **103** when the DC input voltage Vs is a high voltage (120%) when the load is rated

[0061] When the resonant current Iz is not flowing, the turn-on time T1 of the converter **102** is determined in accordance with the ratio of the DC input voltage Vs and the DC output voltage Vd. To control the DC output voltage Vd to be constant, it can be simply considered that the turn-on time T1 of the semiconductor devices constituting the converter **102** is inversely proportional to the magnitude of the DC input voltage Vs. However, the magnitude of the resonant current Iz is proportional to the DC input voltage Vs as shown in FIG. **4**. Since the energy transferred by the resonant current Iz is proportional to the square of the DC input voltage Vs, the turn-on time T1 of the semiconductor devices constituting the converter **102** becomes shorter than a value that is inversely proportional to the magnitude of the DC input voltage Vs as the DC input voltage Vs is increased. When the load is rated, the load current Id is maintained constant by adjusting the turn-on time T1 of the semiconductor devices constituting the converter **102** in accordance with the DC input voltage Vs.

[0062] FIG. **5** shows an example of the operation waveform of the DC power supply according to the present invention. FIG. **5** shows a waveform in a mode where the second PI controller **209** shown in FIG. **2** is operating. In FIG. **5**, the following signals are shown from the top.

(1) the secondary current I2 of the transformer **103** and the load current Id when the DC input voltage Vs is a rated voltage when a load is rated

(2) the secondary current I2 of the transformer **103** and the load current Id when the DC input voltage Vs is the rated voltage when a load is light (50%)

[0063] When the resonant current Iz does not flow, the turn-on time T1 of the semiconductor devices constituting the converter **102** is constant irrespective of the magnitude of the load current Id. While the converter **102** is on, the load current Id is increased in accordance with the DC input voltage Vs, the DC output voltage Vd, and the inductance of the filter reactor **108**. While the converter **102** is off, the load current Id is decreased in accordance with the DC output voltage Vd and the inductance of the filter reactor **108**. The state where the increased amount of the load current Id equals to the decreased amount is a steady state. The turn-on time T1 of the semiconductor devices constituting the converter **102** does not depend on the magnitude of the load current Id.

[0064] The energy transferred by the resonant current Iz is proportional to the square of the DC input voltage Vs. Accordingly, when the load is light, the turn-on time T**1** of the semiconductor devices constituting the converter **102** is required to be shorter than that when the load is rated.

[0065] FIG. **6** shows an example of the operation waveform of the DC power supply according to the present invention. In FIG. **6**, the following signals are shown from the top.

(1) the secondary current I**2** of the transformer **103** and the load current Id when the DC input voltage Vs is a high voltage (120%) when a load is rated

(2) the secondary current I**2** of the transformer **103** and the load current Id when the DC input voltage Vs is a high voltage (120%) when a load is light (50%)

(3) the secondary current I**2** of the transformer **103** and the load current Id when the DC input voltage Vs is a high voltage (120%) when a load is light (20%)

[0066] When the load becomes light, the supplied power is adjusted by controlling the turn-on time T**1** of the semiconductor devices constituting the converter **102** to be shorter than that when the load is rated. The energy transferred by the resonant current Iz is proportional to the square of the DC input voltage Vs. Accordingly, even when the turn-on time T**1** of the semiconductor devices constituting the converter **102** is shortened, the turn-on time T**1** cannot be lower than the lower limit value T**1**min of the turn-on time of the semiconductor devices constituting the converter **102** if the DC input voltage Vs is high. Thus, it is impossible to further reduce the supplied power. At this time, the supplied power can be adjusted by setting the converter control cycle Tc of the converter **102** to be longer. FIG. **6** shows a waveform in a mode where the first PI controller **208** shown in FIG. **2** is operating.

[0067] To secure a period for sampling and holding the first to third A/D converters **200** to **202**, the lower limit value T**1**min of the turn-on time of the semiconductor devices constituting the converter **102** is required to be larger than the sum of ¾ of the resonant cycle obtained by the electrostatic capacitance of the resonant capacitor **107** and the circuit inductance and ½ of the resonant cycle obtained by the electrostatic capacitance of the snubber capacitor **109** and the circuit inductance.

[0068] **100**: DC voltage source
[0069] **101**: first voltage sensor
[0070] **102**: converter
[0071] **103**: transformer
[0072] **104**: current sensor
[0073] **105**: rectifier circuit
[0074] **106**: resonant switch
[0075] **107**: resonant capacitor
[0076] **108**: filter reactor
[0077] **109**: snubber capacitor
[0078] **110**: snubber diode
[0079] **111**: second voltage sensor
[0080] **112**: filter capacitor
[0081] **113**: load
[0082] **114**: controller
[0083] **200**: first A/D converter
[0084] **201**: second A/D converter
[0085] **202**: third A/D converter
[0086] **203**: first subtractor
[0087] **204**: first PI controller
[0088] **205**: second subtractor
[0089] **206**: A contact switch
[0090] **207**: B contact switch
[0091] **208**: second PI controller
[0092] **209**: third PI controller
[0093] **210**: first adder
[0094] **211**: second adder
[0095] **212**: function table
[0096] **213**: limiter
[0097] **214**: pulse controller
[0098] G**1** to G**4**: gate signals of the semiconductor devices Q**1** to Q**4** constituting the converter **102**
[0099] Gz: gate signal of the semiconductor device Qz constituting the resonant switch **106**
[0100] I**1**: primary current
[0101] I**2**: secondary current
[0102] Id: load current
[0103] Id*: load current command
[0104] Id': load current estimated value
[0105] Ir: rectifier diode current
[0106] Is: snubber current
[0107] Iz: resonant current
[0108] T**1**: turn-on time of the semiconductor device constituting the converter **102**
[0109] T**1**min: lower limit value of the turn-on time of the semiconductor device constituting the converter **102**
[0110] T**1***: turn-on time command of the semiconductor device constituting the converter **102**
[0111] T**2**: turn-on time of the semiconductor device constituting the resonant switch **106**
[0112] Tad: trigger signal of the A/D converter
[0113] Tc*: initial value of the converter control cycle
[0114] Tc: converter control cycle
[0115] Q**1** to Q**4**: semiconductor devices constituting the converter **102**
[0116] Qz: semiconductor device constituting the resonant switch **106**
[0117] UF: underflow flag
[0118] Vd*: DC output voltage command
[0119] Vd: DC output voltage
[0120] Vr: rectifier diode voltage
[0121] Vs: DC input voltage

What is claimed is:

1. A DC power supply including a DC voltage source, a converter for converting DC power outputted from the DC voltage source to AC power, a transformer for inputting the AC power outputted from the converter, a rectifier circuit for converting the AC power outputted from the transformer to DC power; a resonant circuit composed of a resonant switch and a resonant capacitor connected in parallel to a DC output side of the rectifier circuit; a filter reactor and a filter capacitor for smoothing the DC power outputted from the rectifier circuit, a snubber circuit connected in parallel to the filter capacitor, and a load connected in parallel to the filter capacitor, the DC power supply comprising:

a first voltage sensor for detecting an output voltage of the DC voltage source;

a second voltage sensor for detecting a voltage of the filter capacitor;

a current sensor for detecting an input current or an output current of the transformer; and

a controller for inputting output signals of the first voltage sensor, second voltage sensor, and current sensor, and outputting a signal that controls a gate pulse of a plurality of semiconductor devices constituting the converter and a gate pulse of a semiconductor device constituting

the resonant switch and a signal that adjusts detection timings of the first voltage sensor, second voltage sensor, and current sensor.

2. The DC power supply according to claim **1**, wherein the snubber circuit includes a diode bridge of a snubber diode and a snubber capacitor for connecting an output of the snubber diode and a DC output side of the rectifier circuit.

3. The DC power supply according to claim **1**, wherein the controller for the gate pulse includes: first controlling means for adjusting supplied power by adjusting a gate pulse width in accordance with a sensor input while an operating frequency of the converter is maintained constant; and second controlling means for adjusting the supplied power by adjusting the operating frequency of the converter in accordance with the sensor input while the gate pulse width of the converter is maintained constant.

4. The DC power supply according to claim **3**, wherein the gate pulse width of the converter has a predetermined lower limit value and means for switching between the first controlling means and the second controlling means based on the lower limit value is provided.

5. The DC power supply according to claim **4**, wherein the lower limit value of the gate pulse width of the converter is set to be larger than a sum of ¾ of a resonant cycle obtained by an electrostatic capacitance of the resonant capacitor and a circuit inductance and ½ of a resonant cycle obtained by an electrostatic capacitance of the snubber capacitor and the circuit inductance.

6. The DC power supply according to claim **2**, wherein the controller for controlling the gate signal includes means for inputting an output signal of the current sensor and performing sampling and holding in synchronization with an operating frequency of the converter after ½ of a resonant cycle obtained by an electrostatic capacitance of the snubber capacitor and a circuit inductance from turn-on of the converter and before ¾ of a resonant cycle obtained by an electrostatic capacitance of the resonant capacitor and the circuit inductance from turn-off.

7. The DC power supply according to claim **2**, wherein the controller for controlling the gate signal includes: first controlling means for adjusting supplied power by adjusting a gate pulse width in accordance with a sensor input while an operating frequency of the converter is maintained constant; second controlling means for adjusting the supplied power by adjusting the operating frequency of the converter in accordance with the sensor input while the gate pulse width of the converter is maintained constant; means for switching between the first controlling means and the second controlling means based on a lower limit value that is larger than a sum of ¾ of a resonant cycle obtained by an electrostatic capacitance of the resonant capacitor and a circuit inductance and ½ of a resonant cycle obtained by an electrostatic capacitance of the snubber capacitor and the circuit inductance; and means for inputting an output signal of the current sensor and performing sampling and holding in synchronization with an operating frequency of the converter after ½ of the resonant cycle obtained by the electrostatic capacitance of the snubber capacitor and the circuit inductance from turn-on of the converter and before ¾ of the resonant cycle obtained by the electrostatic capacitance of the resonant capacitor and the circuit inductance from turn-off.

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