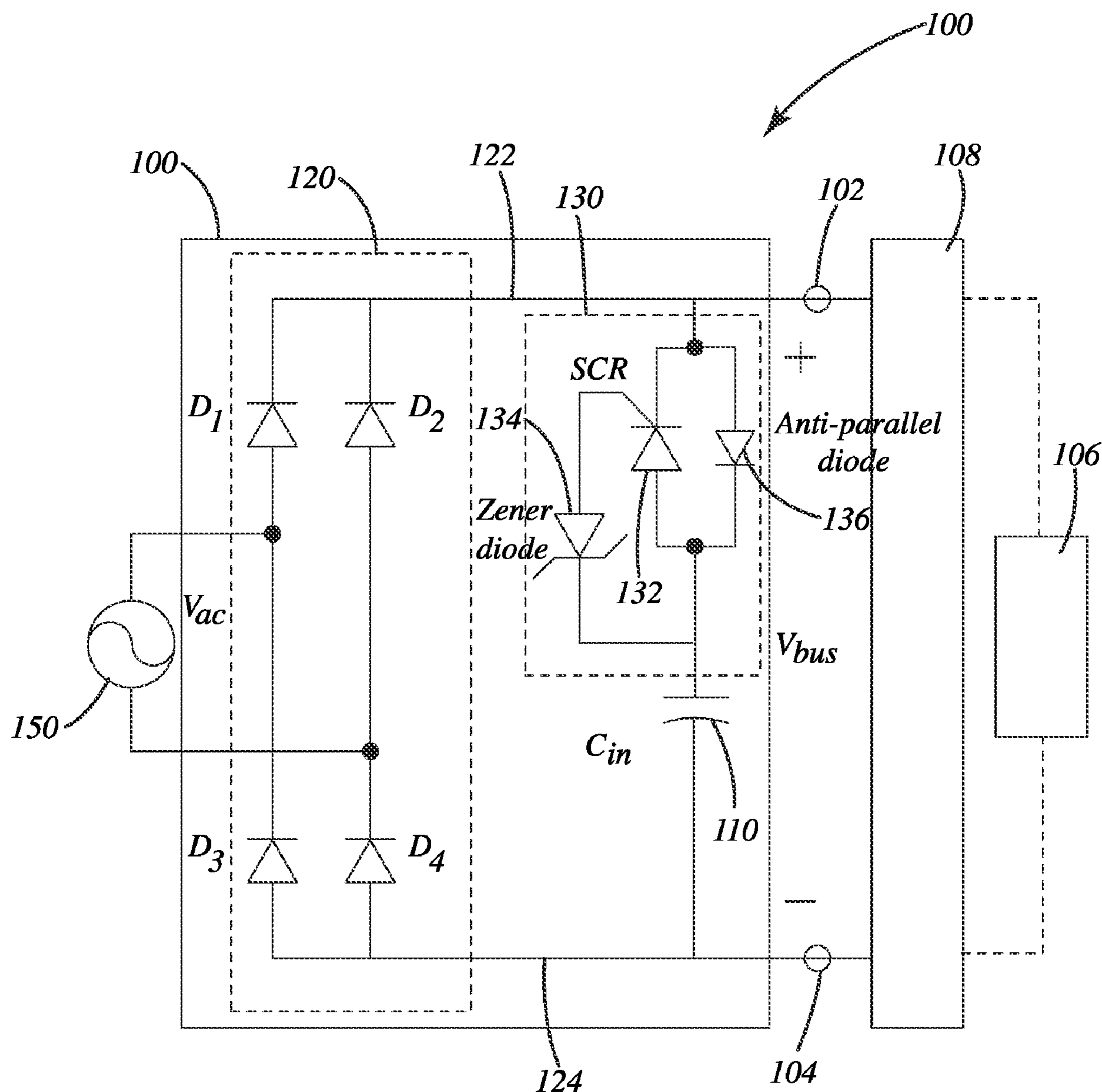




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A rectifier for use in a power supply is provided, including a capacitor charge control circuit operable to enable reduction in bulk capacitance.



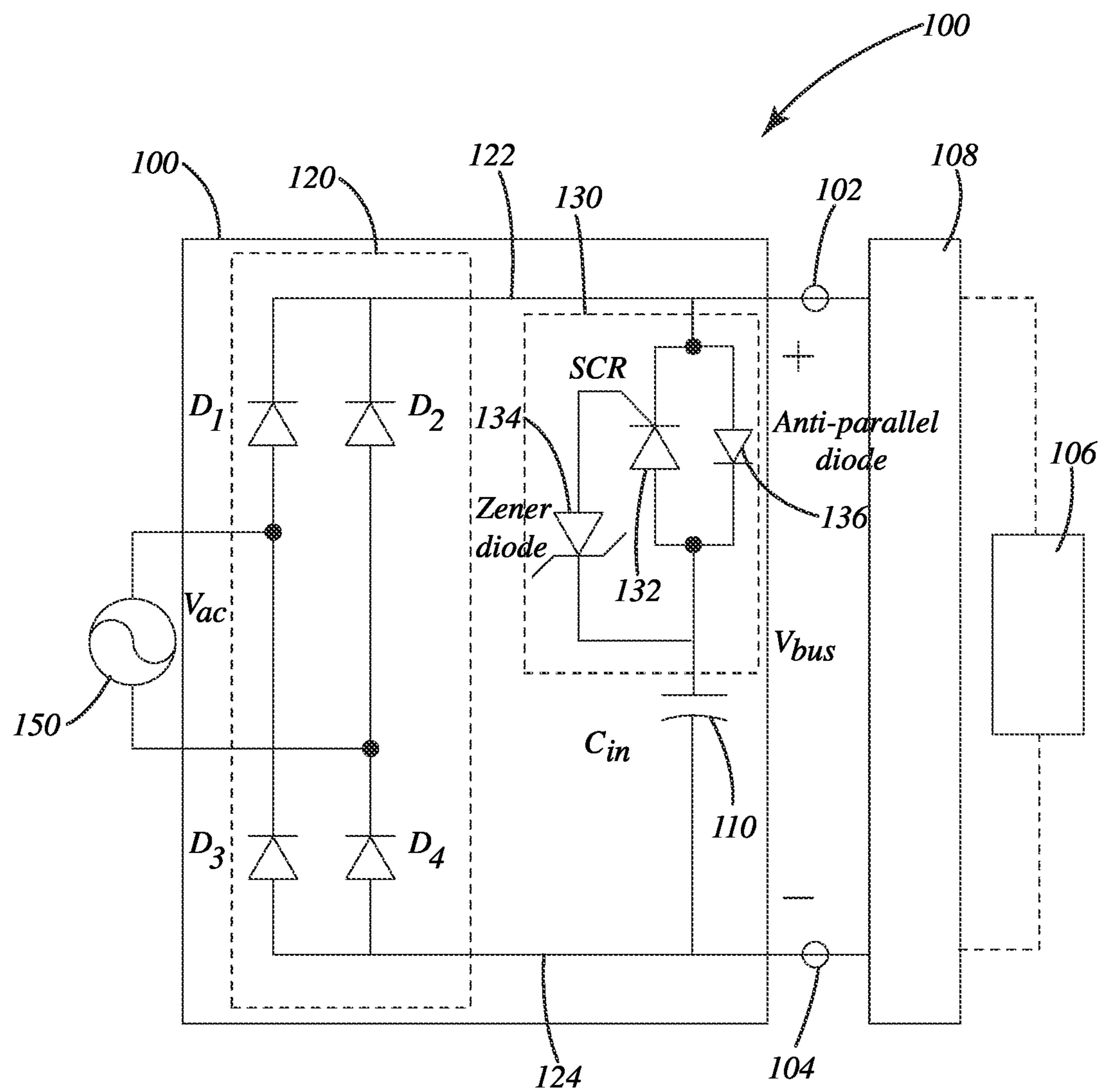


Fig. 1

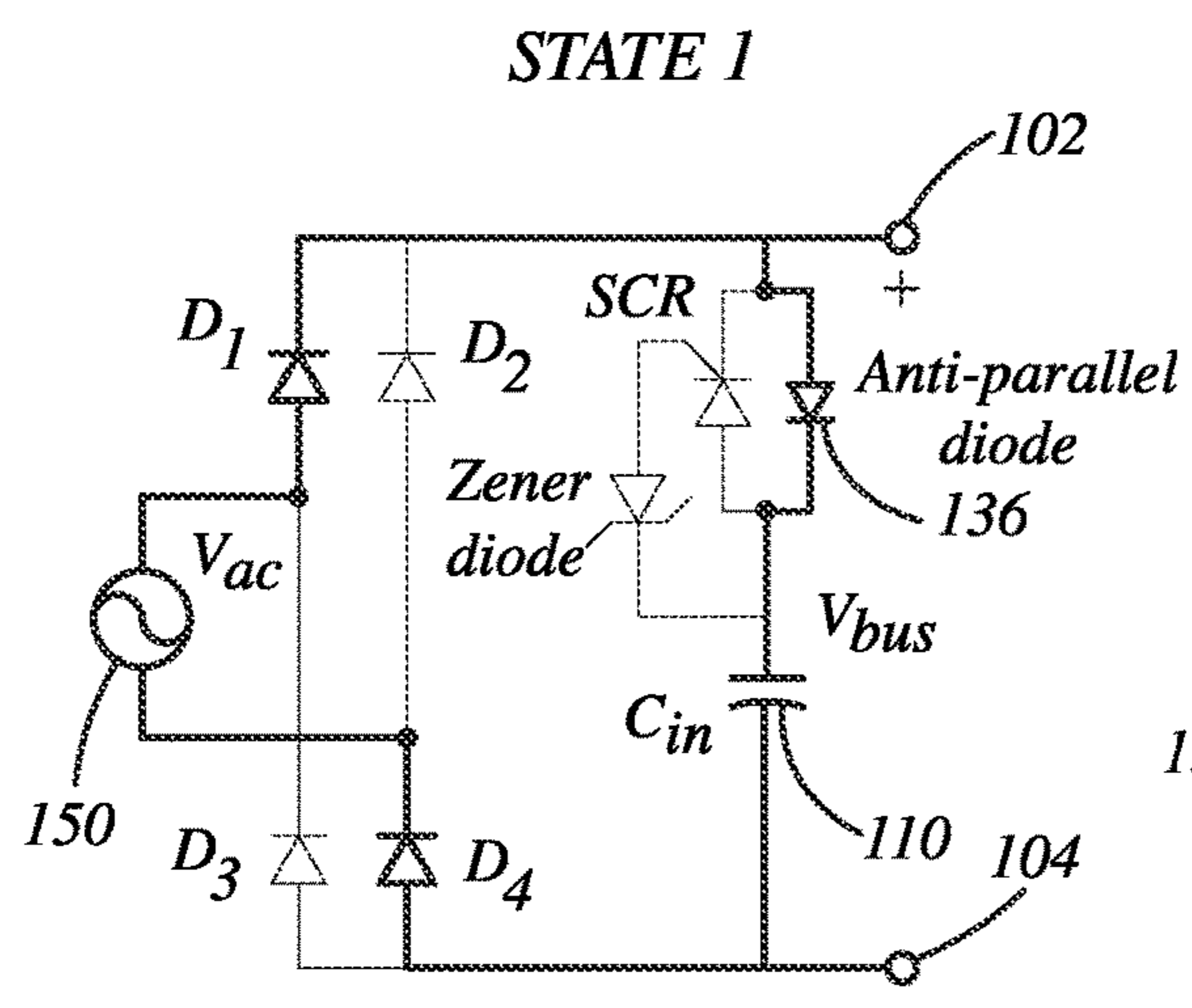


Fig. 2

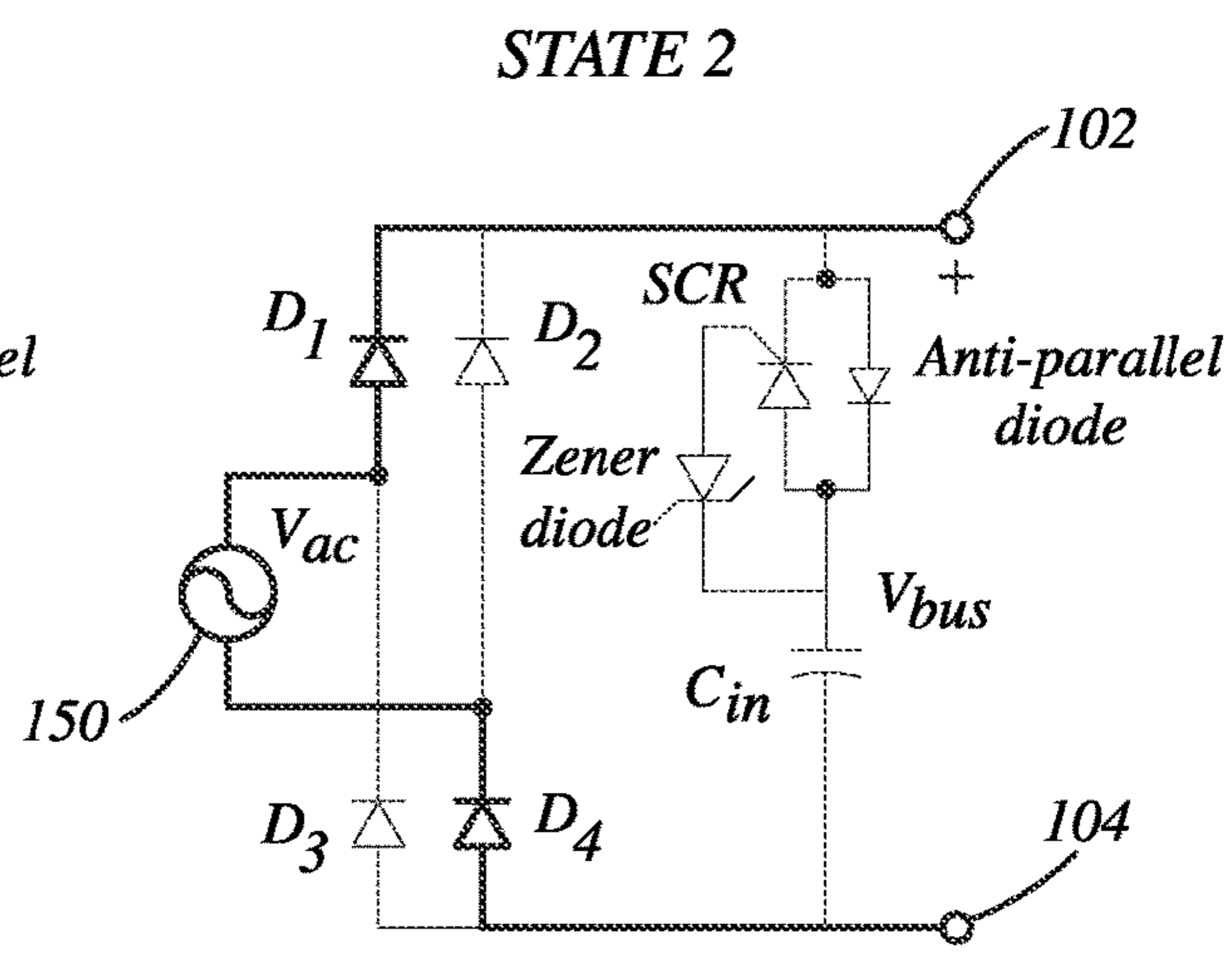


Fig. 3

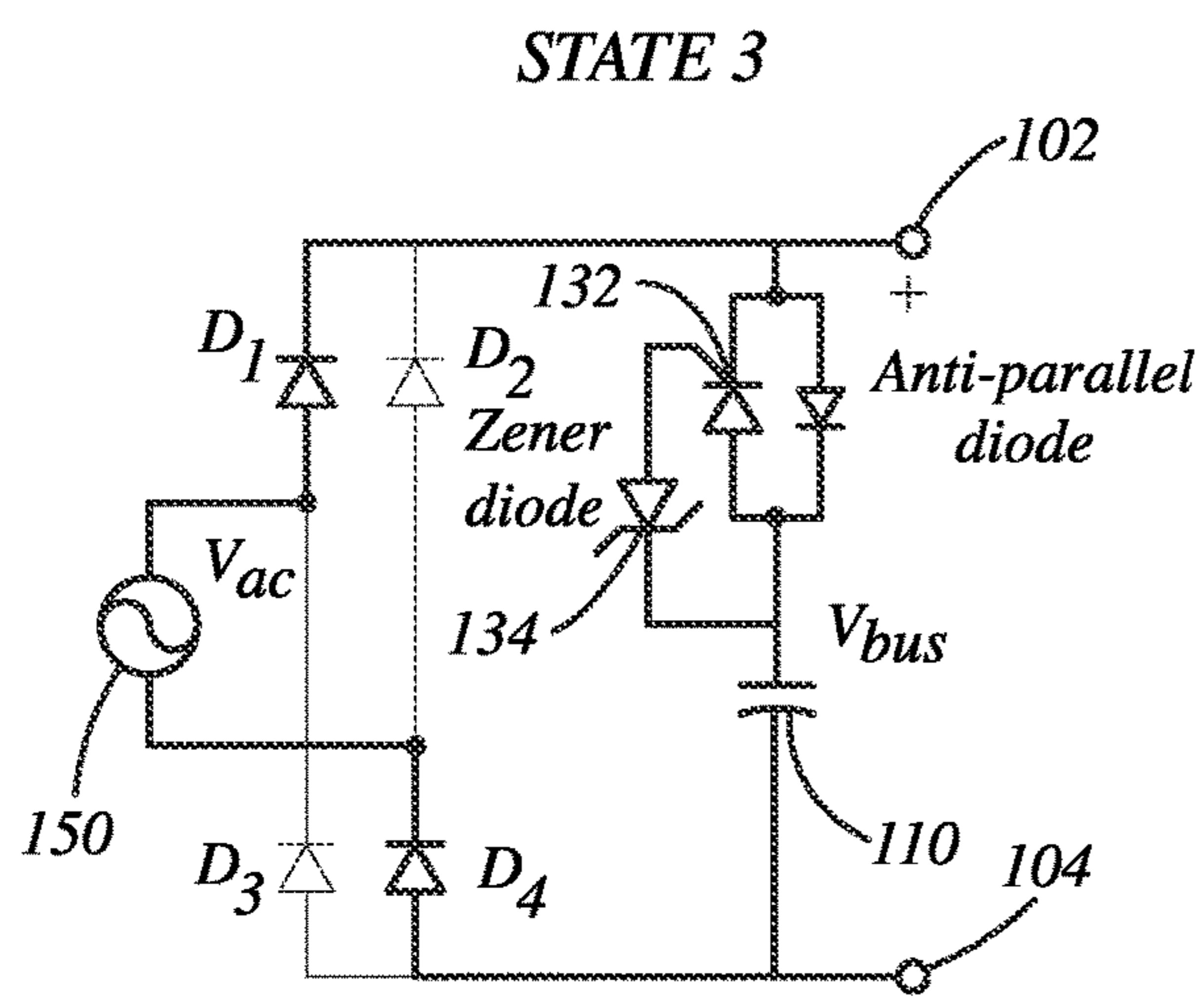


Fig. 4

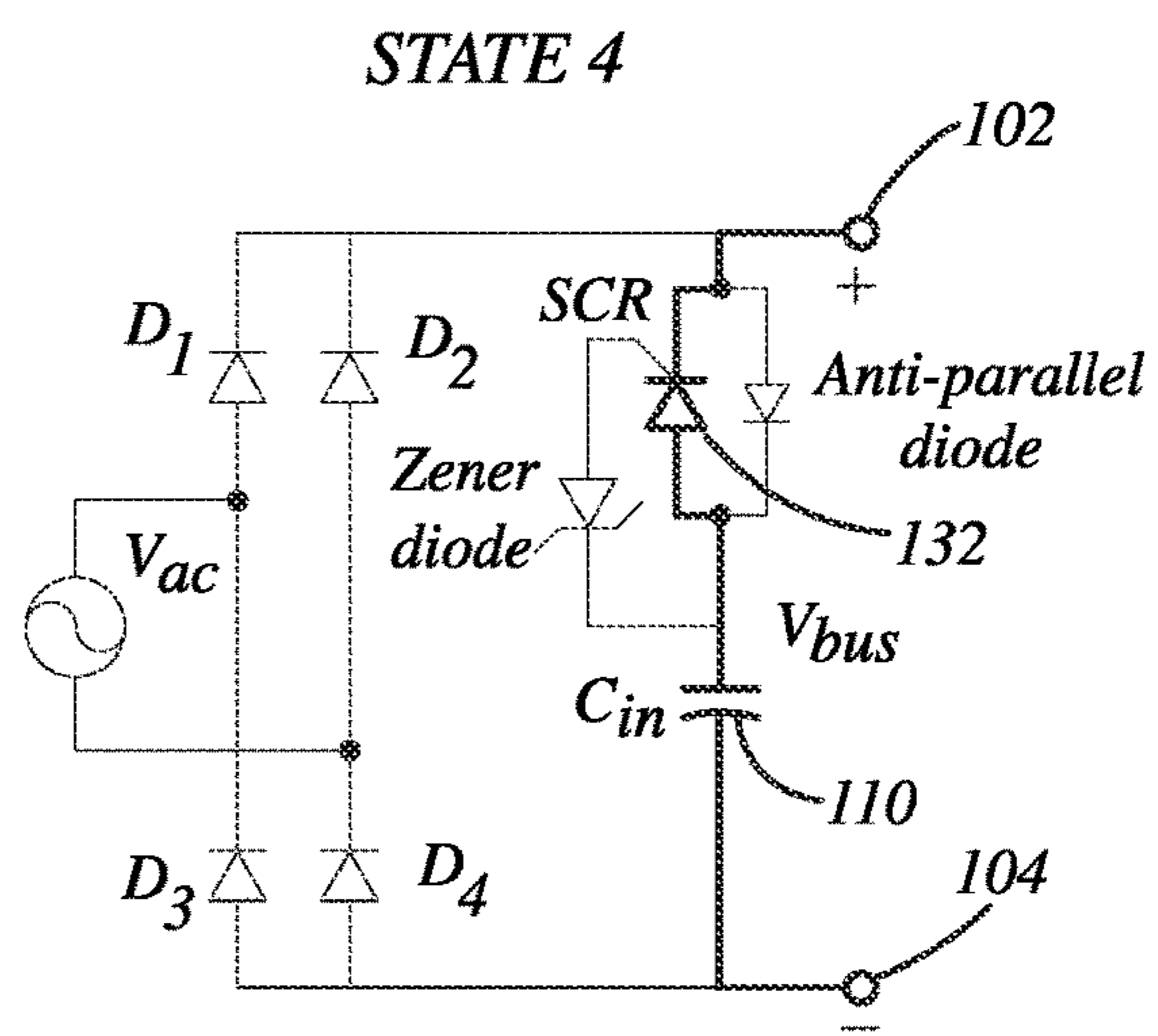


Fig. 5

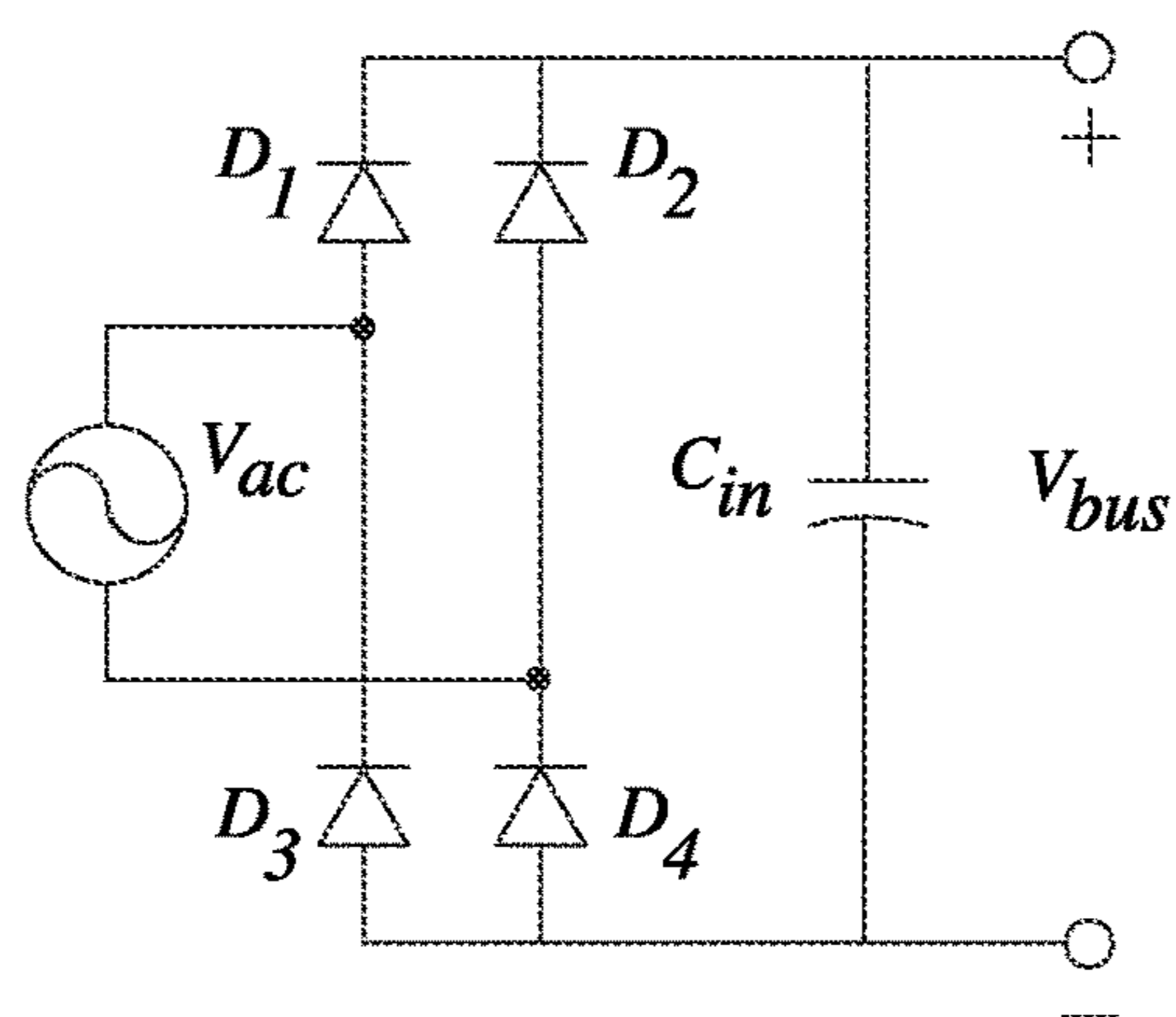


Fig. 6 (Prior Art)

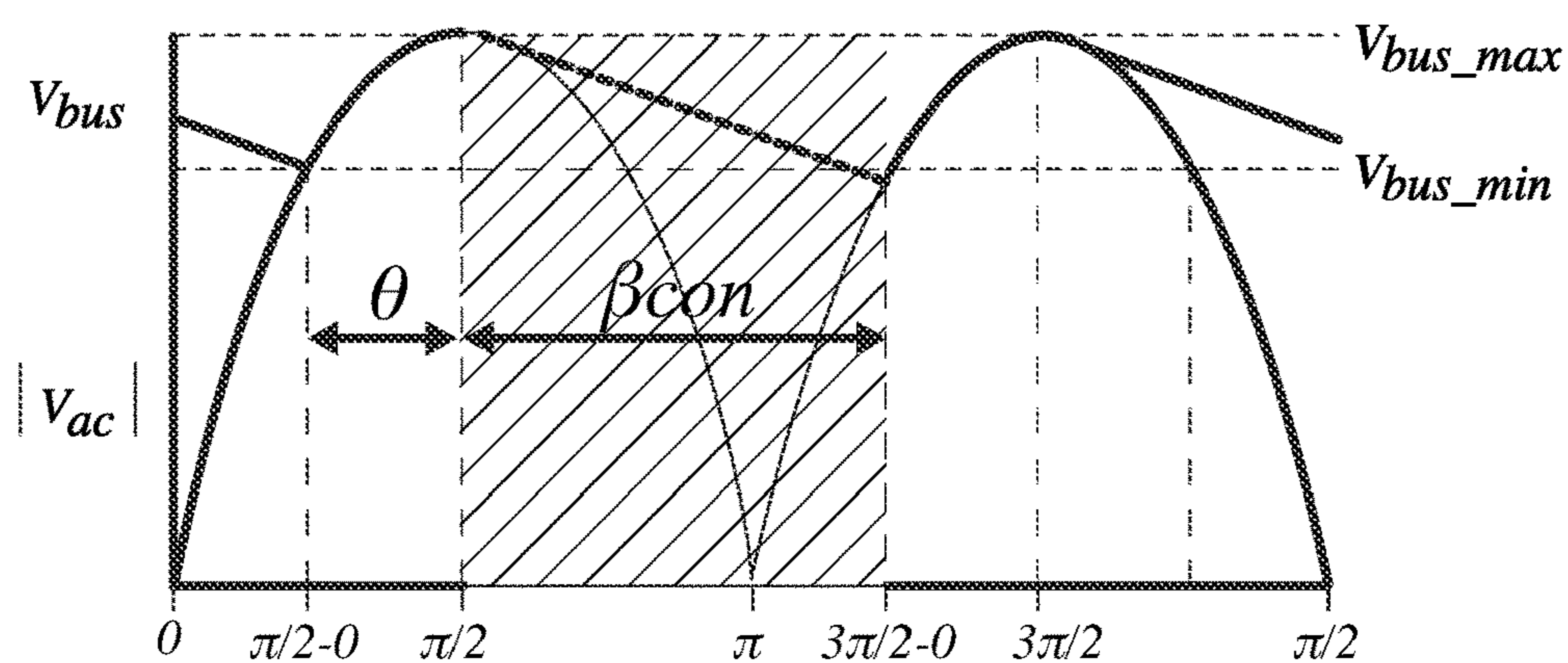


Fig. 7 (Prior Art)

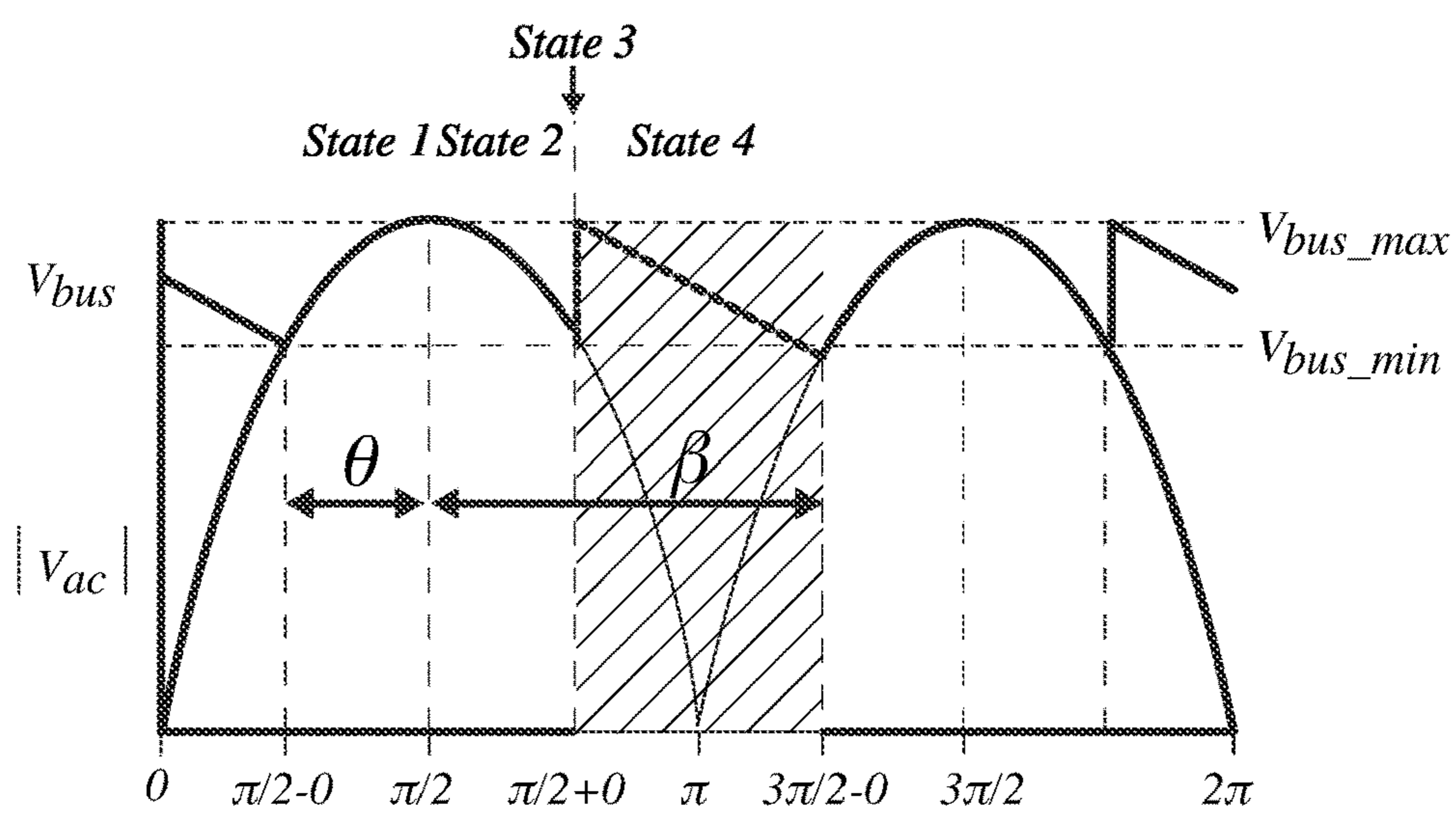


Fig. 8

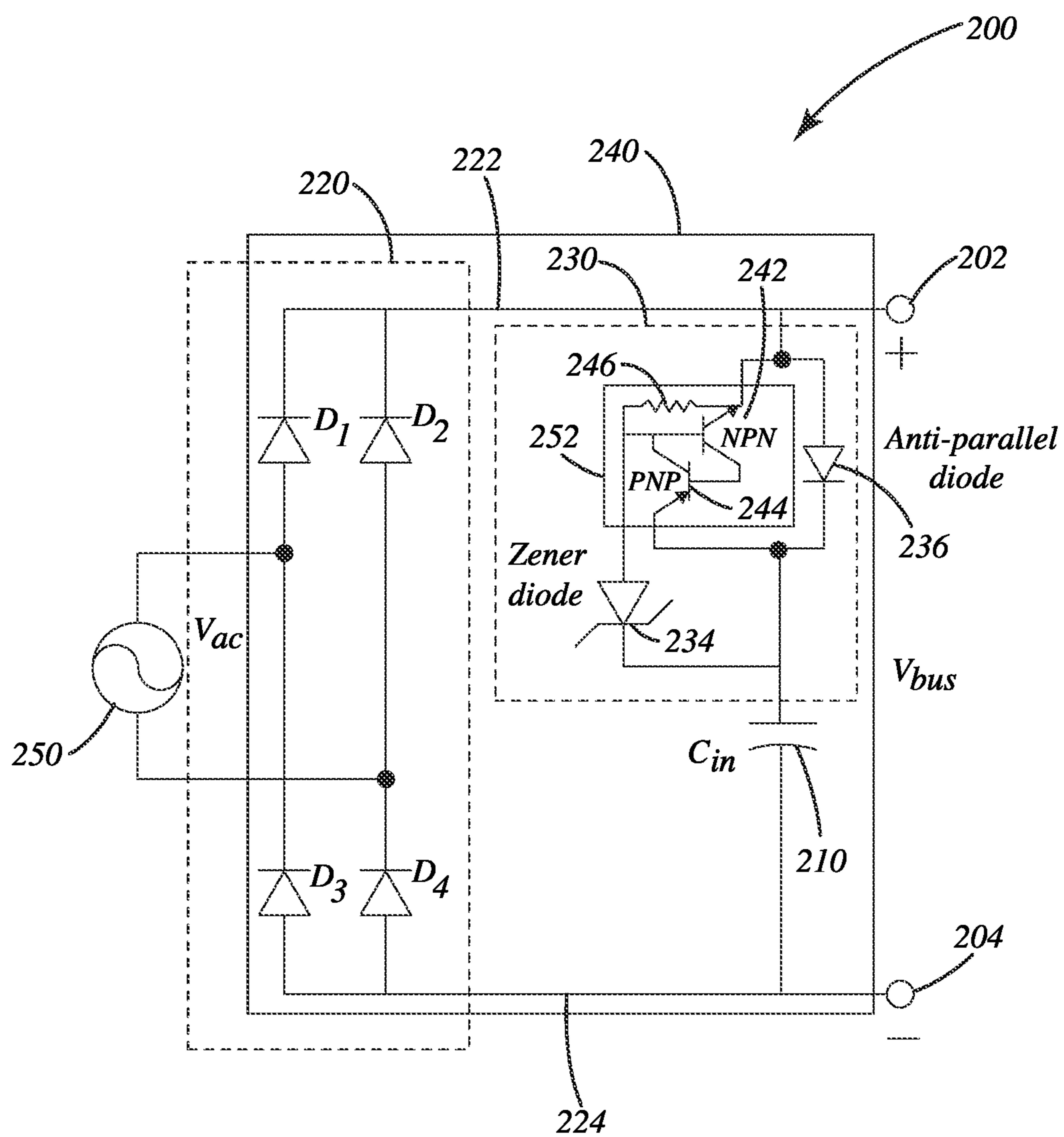
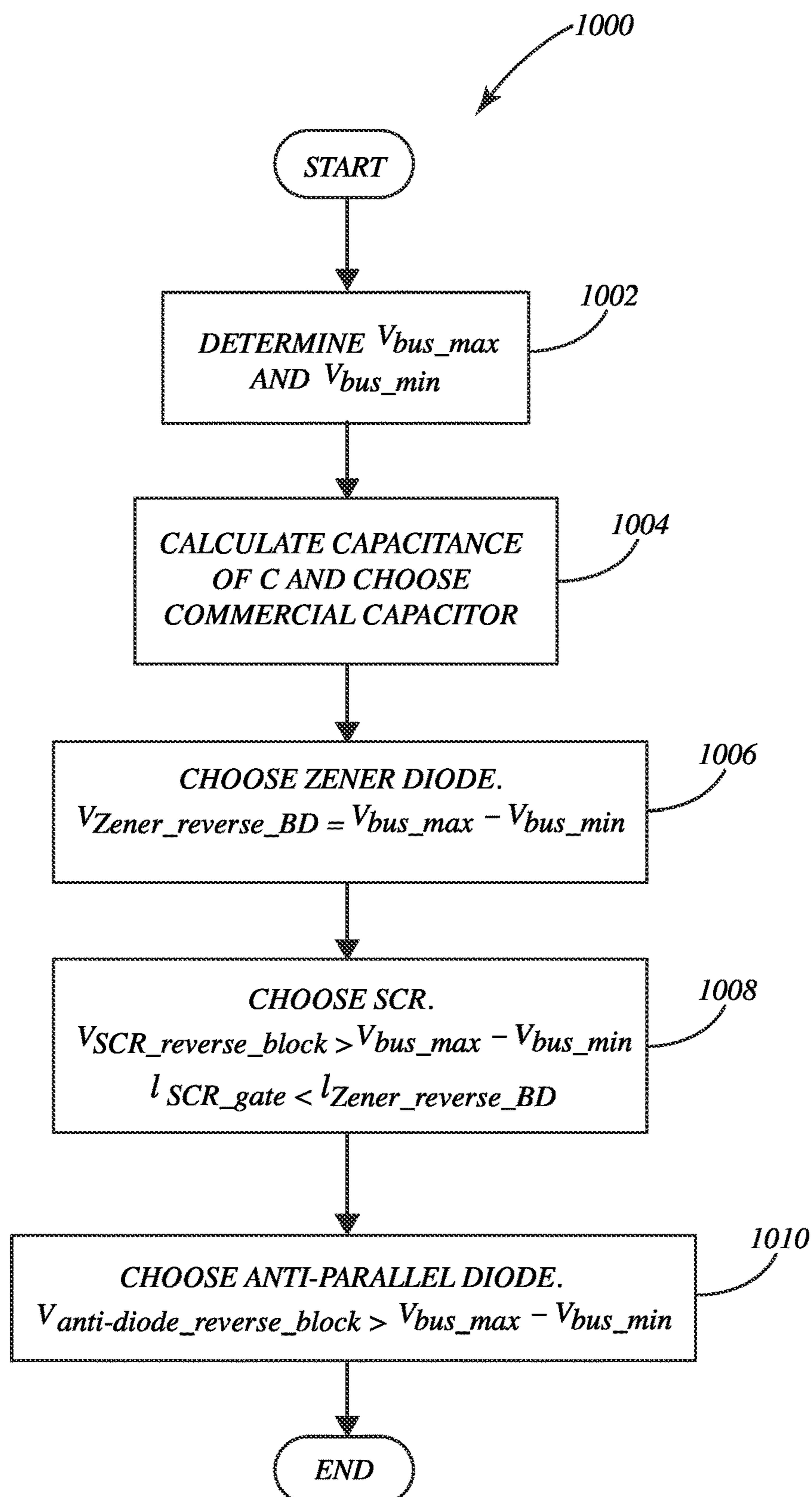


Fig. 9

*Fig. 10*

SYSTEM FOR BULK CAPACITANCE REDUCTION

SYSTEM FOR BULK CAPACITANCE REDUCTION STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0001] This invention was made with government support under Contract No. DE-AC05-00OR22725 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

FIELD OF INVENTION

[0002] The present disclosure relates to the field of power generation, and more particularly toward circuitry for reducing bulk capacitance in a power supply.

BACKGROUND

[0003] Universal Serial Bus Power Delivery (USB-PD) aims to unify charging protocols for a wide range of devices including smartphones, tablets, and laptops, with conventional power supply configurations capable of supplying power up to 240 W. The market is currently driving toward smaller USB-PD solutions.

[0004] Wide bandgap (WBG) devices with higher breakdown voltage and smaller on-state resistance have been adopted in conventional systems for high-power-density high-frequency applications. The rapid progress in WBG devices has enabled power converters in USB-PD solutions to switch at a higher frequency and reduce the size of magnetic components and output capacitors. For instance, gallium nitride (GaN) technology, a type of WBG device, has been adopted for this purpose and operates by switching at a higher frequency, thus reducing the size of magnetic and output capacitors.

[0005] However, despite advancements in switching technology and density, the bulk electrolytic capacitors in conventional power supplies remain large because the bulk capacitor is line-frequency dependent. For instance, the line-frequency dependent bulk capacitor in a conventional AC-DC rectifier remains a challenge in shrinking the total system size because higher switching frequency does not result in smaller bulk electrolytic capacitors. For conventional constructions with a power rating less than 75 W, the bulk capacitors can take as much as 35% of the total system volume, where power factor correction is not needed. Conventional research efforts have focused on reducing bulk-capacitor reduction in high power kilowatt applications, which require multiple switches, drivers, sensing and control circuitry, and even micro-processors. These conventional efforts, therefore, incur high complexity and cost, whereas bulk-capacitor reduction in low power and cost-sensitive AC-DC applications has largely been ignored.

[0006] One conventional effort involves use of a MinE-CAP integrated circuit (IC) from power integrations as a bulk-capacitor volume reduction solution that divides one large electrolytic high-voltage capacitor into one small electrolytic or ceramic high-voltage capacitor paralleled with one low-voltage electrolytic capacitor, attempting to minimize the total system volume by mainly operating the low-voltage capacitor at low AC line voltage. However, to realize the capacitors' operating conversion under different AC line voltages, the MinE-CAP IC solution utilizes an

active switch connected in series with the MinE-CAP IC, resulting in higher system complexity.

[0007] This and other conventional efforts to reduce the bulk capacitor require complicated control, dramatically increase cost, and compromise reliability.

SUMMARY

[0008] In general, one innovative aspect of the subject matter described herein can be embodied in self-driven circuitry to be connected in series with a bulk capacitor between first and second output ports of a rectifier. The self-driven circuitry may include a thyristor circuit with an anode terminal, a cathode terminal, and a gate terminal. The anode terminal may be connected to a first connector of the bulk capacitor that opposes a second connector of the bulk capacitor that is connected to the second output port. The cathode terminal may be connected to the first output port. The self-driven circuitry may include a diode connected antiparallel to the thyristor circuit between the anode terminal and the cathode terminal, and a Zener diode connected parallel to the thyristor circuit between the gate terminal and the anode terminal.

[0009] The foregoing and other embodiments can each optionally include one or more of the following features, alone or in combination. In particular, one embodiment includes all the following features in combination.

[0010] In some embodiments, the rectifier may include a full diode-bridge.

[0011] In some embodiments, thyristor circuit may include a silicon-controlled rectifier (SCR), where the SCR includes a cathode connected to the cathode terminal, an anode connected to the anode terminal, and a gate connected to the gate terminal.

[0012] In some embodiments, the thyristor circuit may include 1) an NPN transistor for which an emitter of the NPN transistor is connected to the cathode terminal, 2) a PNP transistor for which an emitter of the PNP transistor is connected to the anode terminal, a collector of the PNP transistor being connected to a gate of the NPN transistor, a gate of the PNP transistor being connected to a collector of the NPN transistor, and 3) a driving resistor connected between the gate of the NPN transistor and the emitter of the NPN transistor.

[0013] In some embodiments, a AC-DC converter may include a rectifier stage operable to output DC voltage. The rectifier stage may include a rectifier according to one embodiment with input ports to be connected to an AC-voltage source. The rectifier may include the first and second output ports to deliver output voltage based on power from the AC-voltage voltage. The bulk capacitor may include a first terminal connected to the second output port. Self-driven circuitry may be connected between the first output port and a second terminal of the bulk capacitor that opposes the first terminal of the bulk capacitor, where the AC-DC converter may be configured to deliver the DC voltage over a voltage range between a maximum voltage V_{MAX} and a minimum voltage V_{MIN} .

[0014] In some embodiments, the rectifier may include a full diode-bridge.

[0015] In some embodiments, the rectifier stage may include a first stage output and a second stage output. The cathode terminal of the self-driven circuitry may be connected to the first stage output. The second output port of the

rectifier may be connected to the second stage output. The DC voltage may be output from the first and second stage outputs.

[0016] In some embodiments, the Zener diode may be configured to have a reverse voltage that is substantially equal to the difference $V_{MAX}-V_{MIN}$.

[0017] In some embodiments, an SCR of the thyristor circuit may be configured to include an off-state voltage that is larger than the difference $V_{MAX}-V_{MIN}$, and a gate current $ISCR_GATE$ that is smaller than a reverse break-down current of the Zener diode $IZENER_REVERSE$.

[0018] In some embodiments, the DC blocking voltage of the diode may be configured to be larger than the difference $V_{MAX}-V_{MIN}$.

[0019] In some embodiments, a capacitance value of the bulk capacitor may substantially corresponds to

$$\frac{2P_o\beta_{new}}{2\pi f_{line}(V_{MAX}^2 - V_{MIN}^2)}, \text{ where } \beta_{new} = \pi - 2 \cos^{-1}\left(\frac{V_{MIN}}{V_{MAX}}\right),$$

and where f_{line} is the frequency of the AC-voltage source, and P_o is the output power of the rectifier.

[0020] In some embodiments, the AC-DC converter may be a GaN-based active-clamp flyback AC-DC converter for universal serial bus power delivery charger applications.

[0021] In general, one innovative aspect of the subject matter described herein can be embodied in a capacitor charge controller operable to control charge and discharge of a bulk capacitor. The bulk capacitor may include a first capacitor terminal and a second capacitor terminal. The capacitor charge controller may include a switching circuit with a first terminal, a second terminal, and an input terminal, where the first terminal may be operably coupled to a first rectifier output of a rectifier, and where the second terminal may be operably coupled to the first capacitor terminal of the bulk capacitor. The second capacitor terminal of the bulk capacitor may be operably coupled to a second rectifier output of the rectifier. The capacitor charge controller may include a diode connected in parallel to the switching circuit and including a diode anode terminal and a diode cathode terminal. The diode anode terminal may be operably coupled to the first terminal of the switching circuit, and the diode cathode terminal may be operably coupled to the second terminal of the switching circuit. The capacitor charge controller may include a Zener diode operably coupled to the input terminal of the switching circuitry and the first capacitor terminal of the bulk capacitor.

[0022] The foregoing and other embodiments can each optionally include one or more of the following features, alone or in combination. In particular, one embodiment includes all the following features in combination.

[0023] In some embodiments, the switching circuit may include a thyristor with a thyristor anode, a thyristor cathode, and gate input, where the thyristor cathode may be coupled to the first terminal and the thyristor anode is coupled to the second terminal, and where the gate input may be coupled to the input terminal.

[0024] In some embodiments, the Zener diode may control operation of the thyristor via the gate input.

[0025] In some embodiments, the diode may be connected antiparallel to the thyristor.

[0026] In some embodiments, the switching circuit may include an NPN transistor for which an emitter of the NPN transistor is connected to the cathode terminal, and a PNP transistor for which an emitter of the PNP transistor is connected to the anode terminal, a collector of the PNP transistor being connected to a gate of the NPN transistor, a gate of the PNP transistor being connected to a collector of the NPN transistor. The switching circuit may include a driving resistor connected between the gate of the NPN transistor and the emitter of the NPN transistor.

[0027] In some embodiments, the capacitor charge controller may be self-driven.

[0028] In some embodiments, the capacitor charge controller and the bulk capacitor may be provided in series between first and second output ports of a rectifier, where the rectifier may be operable to receive AC-voltage from an AC power source, and where the rectifier, the capacitor charge controller, and the bulk capacitor may be operable to output DC-voltage.

[0029] In some embodiments, the Zener diode may be configured to have a reverse voltage that is substantially equal to the difference $V_{MAX}-V_{MIN}$.

[0030] Before the embodiments of the invention are explained in detail, it is to be understood that the invention is not limited to the details of operation or to the details of construction and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention may be implemented in various other embodiments and of being practiced or being carried out in alternative ways not expressly disclosed herein. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of “including” and “comprising” and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items and equivalents thereof. Further, enumeration may be used in the description of various embodiments. Unless otherwise expressly stated, the use of enumeration should not be construed as limiting the invention to any specific order or number of components. Nor should the use of enumeration be construed as excluding from the scope of the invention any additional steps or components that might be combined with or into the enumerated steps or components. Any reference to claim elements as “at least one of X, Y and Z” is meant to include any one of X, Y or Z individually, and any combination of X, Y and Z, for example, X, Y, Z; X, Y; X, Z; and Y, Z.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] FIG. 1 shows a power supply apparatus in accordance with one embodiment.

[0032] FIG. 2 shows a first state of the power supply apparatus of FIG. 1.

[0033] FIG. 3 shows a second state of the power supply apparatus of FIG. 1.

[0034] FIG. 4 shows a third state of the power supply apparatus of FIG. 1.

[0035] FIG. 5 shows a fourth state of the power supply apparatus of FIG. 1.

[0036] FIG. 6 shows a prior art rectification circuit.

[0037] FIG. 7 shows waveforms with respect to the prior rectification circuit of FIG. 6.

[0038] FIG. 8 shows waveforms with respect to the power supply apparatus of FIG. 1.

[0039] FIG. 9 shows an alternative embodiment of a power supply apparatus according to the present disclosure.

[0040] FIG. 10 depicts a method in accordance with one embodiment.

DETAILED DESCRIPTION

[0041] A self-driven circuit with three components, optionally only three, may be provided in one embodiment to automatically realize line-conduction extension and reduce the bulk capacitance. For instance, the self-driven circuit may utilize a self-driven thyristor configuration that includes only three components in total. No extra control circuit may be needed. In this manner, one embodiment according to the present disclosure may provide a simple and inexpensive implementation for reducing bulk capacitance over conventional approaches. It should be understood that the present disclosure is not limited to a three-component configuration, and that alternative embodiments may include greater or fewer components.

[0042] The self-drive circuitry in one embodiment can be used for power supplies or power adapters, such as USB power delivery chargers, USB power delivery wall sockets, LED lighting, etc., and in a variety of fields, such as information technology, communications, electronics, and energy and utilities.

[0043] A power supply apparatus in accordance with one embodiment is depicted in FIG. 1 and generally designated 100. The power supply apparatus 100 is configured to receive power from a power source 150, such as an AC or DC power source. The power supply apparatus 100 may be coupled to load 106. The load 106 may vary from application to application, including for example passive and/or active circuitry. The power supply apparatus 100 in one embodiment may include power supply circuitry 108 that is 1) integral to the power supply apparatus 100 and 2) operable to supply power to the load 106, which may be external to the power supply apparatus 100. The power output from first and second ports 102, 104 of the power supply apparatus 100 may correspond to output from a rectifier 160, which may include rectification circuitry 120 and a bulk capacitor 110. The power supply apparatus 100 in accordance with one embodiment may correspond to an AC/DC converter.

[0044] The power supply circuitry 108 in one embodiment may be pass-through circuitry (e.g., pass-through conductors) operable to couple power output from first and second ports 102, 104 to the load 106. Alternatively, the power supply circuitry 108 may be operable to receive power from the first and second ports 102, 104 and to translate the received power into a form usable by the load 106 according to one or more power specifications. As an example, the power supply circuitry 108 may include a switched mode power supply operable to convert high voltage power (e.g., 150V) output from the first and second ports 102, 104 into a low voltage (e.g., 5V DC) usable by the load 106. Additional examples of power supply circuitry 108 are described in U.S. Application No. 63/299,511 filed on Jan. 14, 2022 and U.S. application Ser. No. 18/095,765 filed on Jan. 11, 2023—the disclosures of which are hereby incorporated by reference in their entirety. As another example, the power supply circuitry 108 may be a GaN-based active-claim flyback (ACF) converter.

[0045] The power supply apparatus 100 in one embodiment may be a USB power supply operable to receive AC

power in the form of 120 VAC and to output 5 VDC, and the power output from the first and second ports 102, 104 may correspond to output from the rectifier 160.

[0046] For instance, in the case of the power source 150 being an AC power source, and the power supply circuitry 108 including a switched mode power supply, the switched mode power supply may include switching circuitry operable to convert and regulate DC power for supply to one or more output ports of the power supply apparatus 100. The one or more output ports may be respectively coupled to one or more loads, collectively forming the load 106. For instance, the first output port may be coupled to a first load, and the second output port may be coupled to a second load. The loads may be removably coupled to the ports of the power supply apparatus 100, such as via a connector (e.g., a USB connector).

[0047] In the illustrated embodiment of FIG. 1, the power supply apparatus 100 includes a rectifier 160 operably coupled to the power source 150. The rectifier 160 may include rectification circuitry 120 configured to receive power from the power source 150 and to provide power via a first rectifier port 122 and a second rectifier port 124. In the illustrated embodiment, the rectification circuitry 120 is a full-bridge rectifier with four diodes D1, D2, D3, D4 arranged in a passive rectification configuration—however, it is to be understood that the rectification circuitry 120 may be configured differently depending on the application. As an example, the rectification circuitry 120 may include active rectification circuitry, such as one or more switches that are actively controlled to rectify power received from the power source 150 and output power with respect to the first and second rectifier ports 122, 124.

[0048] The rectifier 160 in the illustrated embodiment includes a capacitor charge controller 130 operable to control charge and discharge of a bulk capacitor 110. The bulk capacitor 110 may include first and second capacitor terminals, where the first capacitor terminal is coupled to the capacitor charge controller 130 and the second capacitor terminal is coupled to one of the first and second ports 102, 104 of the rectifier 160.

[0049] The capacitor charge controller 130 in the illustrated embodiment may be self-driven. For instance, a controller, such as a microcontroller or microprocessor, may be absent from the capacitor charge controller 130. The capacitor charge controller 130 in one embodiment may provide a reliable control circuit that accommodates inrush, surge, and lightning.

[0050] The capacitor charge controller 130 in the illustrated embodiment includes a switching circuit 132, which may be thyristor, such as a silicon controlled rectifier (SCR) device, or circuitry operable to provide similar functionality. The capacitor charge controller 130 may also include a diode 136 connected in parallel to the switching circuit 132, with an anode of the diode 136 coupled to a first terminal of the switching circuit 132 that is also coupled to the first port 102 and a cathode of the diode 136 coupled to a second terminal of the switching circuit 132 that is also coupled to the bulk capacitor 110.

[0051] The parallel arrangement of the diode 136 and the switching circuit 132 may be an anti-parallel configuration, with the devices coupled in parallel but with their polarities reversed. For instance, in the illustrated embodiment, the switching circuit 132 includes an anode, a cathode, and a gate. The anode of the switching circuit 132 may be con-

nected to the cathode of the diode **136**, and the cathode of the switching circuit **132** may be connected to the anode of the diode **136**. In this configuration, the switching circuit **132** and the diode **136** are in parallel but with their polarities reversed, thereby providing an antiparallel configuration.

[0052] The capacitor charge controller **130** may include a Zener diode **134** coupled to a gate of the switching circuit **132**, with the anode of the Zener diode **134** connected to the gate, and the cathode coupled to the anode of the switching circuit **132**.

[0053] To provide context, a conventional rectifier is depicted in the illustrating embodiment of FIG. 6, including full-bridge rectification circuitry (e.g., a diode bridge) and a bulk capacitor coupled to the outputs of the full-bridge rectification circuitry. In this conventional configuration, DC bus voltage is output from the diode bridge by rectifying the AC line voltage from a power source (e.g., utility power from wall outlet). The DC bus voltage is mitigated by the bulk capacitor. In this conventional rectifier, the AC line voltage only supplies the output bus voltage shorter than one-quarter AC line period in a half line cycle, until reaching its maximum value. Meanwhile, the capacitor voltage is charged to the same value as maximum AC line voltage. When AC line voltage is lower than capacitor voltage, the bus voltage is maintained by discharging the bulk capacitor. Thus, bulk capacitors with large capacitance are used in conventional full-bridge rectifiers and use a large amount of space, causing a comparably low power density.

[0054] The rectifier **160** in the illustrated embodiment of FIG. 1 enables use of a much smaller capacitance relative to a conventional full-bridge rectifier with little circuitry (e.g., a capacitor charge controller **130**), thereby enabling much higher power density over conventional constructions. For instance, to reduce the bulk capacitance and system volume, a capacitor charge controller **130** may utilize a self-driven thyristor coupled to a rectification circuitry **120**. In one embodiment, the capacitor charge controller **130** may include an SCR, a Zener diode, and an anti-parallel diode, in series of the bulk capacitor **110** for its automatic connection and AC line voltage supply extension.

[0055] Turning to the illustrated embodiment of FIGS. 2-5, several operational stages of the capacitor charge controller **130** are shown relative to current flow within the power supply apparatus **100**.

[0056] FIG. 2—State 1: Capacitor charging. In the illustrated embodiment of FIG. 2, the bulk capacitor **110** is shown being charged through the anti-parallel diode **136** until the bulk capacitor **110** voltage reaches maximum bus voltage V_{bus_max} (e.g., the voltage across ports **102**, **104**).

[0057] FIG. 3—State 2: Line conduction extension. In the illustrated embodiment of FIG. 3, as AC line voltage drops below its maximum, both the Zener diode **134** and the anti-parallel diode **136** are reverse-biased, preserving the capacitor energy from releasing to the load and leaving the line voltage to supply for an extended conduction angle θ . As a result, the AC line voltage supply angle is doubled from 0 to 2θ compared to the conventional rectifier shown in FIG. 6.

[0058] FIG. 4—State 3: SCR turn-on transient. In the illustrated embodiment of FIG. 4, when the difference of the capacitor voltage and the AC line voltage reaches the reverse breakdown voltage of the Zener diode **134**, which is likely around or equal to $V_{bus_max} - V_{bus_min}$, the breakdown current of the Zener diode **134** turns on the switching circuit

132 (e.g., an SCR), so the bulk capacitor **110** is re-connected into the circuit and starts to supply the bus voltage to the first and second ports **102**, **104**.

[0059] FIG. 5—State 4: Capacitor discharging. In the illustrated embodiment of FIG. 5, as the capacitor **110** discharges, the Zener diode **134** resumes reverse blocking and the gate current of the switching circuitry **132** decreases, but the switching circuitry **132** stays on due to its latching characteristic. The bulk capacitor **110** may supply power to the load **106** until the capacitor voltage drops below a minimum bus voltage V_{bus_min} , where the AC line voltage regains control and the switching circuitry **132** turns off naturally with the forward voltage dropping below its minimum holding-current threshold. The AC line voltage starts to re-charge the capacitor **110** through the forwardly biased anti-parallel diode **136**, which completes one operation cycle.

[0060] In other words, with respect to the operational stages, the switching circuitry **132** (e.g., an SCR) may be turned on by a threshold-setting Zener diode **134** at $V_{bus_max} - V_{bus_min}$ and is turned off naturally after AC line voltage takes over, realizing an automatic connection of the bulk capacitor **110**. Unlike employing active switches to control a connection of the bulk capacitor **110**, the capacitor charge controller **130** may not require additional sensing, control logic, or drivers to achieve operation, enabling a robust, high-density, and low-cost solution.

[0061] Turning to the illustrated embodiment of FIG. 8, the four operational stages are depicted relative to bus voltage and the AC input voltage. For context, these operational stages are described relative to operation shown in FIG. 7 with respect to the conventional rectifier in FIG. 6.

[0062] FIG. 8 shows bus voltage waveforms for the power supply apparatus **100** in the illustrated embodiment of FIGS. 1-5, and FIG. 7 shows bus voltage waveforms for the conventional rectifier of FIG. 6. The waveforms in FIGS. 7 and 8 include the rectified AC line voltage shown as rectified sinusoidal waveforms with a 2π period, with both positive and negative cycles rectified to positive voltage, and with portions of the rectified sinusoidal waveforms shown overlapping the bus voltage in the region between V_{bus_max} and V_{bus_min} . The bus voltages waveforms are shown in the region between V_{bus_max} and V_{bus_min} .

[0063] With respect to operational states (e.g., stages or modes) of the power supply apparatus **100**, the bus voltage waveforms depicted in FIG. 8 overlap the rectified AC line voltage waveforms in states 1 and 2.

[0064] In the illustrated embodiment, V_{bus_max} is equal to the maximum AC line voltage, and V_{bus_min} , which is adjustable by choosing a Zener diode **134** with a different reverse breakdown voltage, and may be decided by the input voltage requirement of the follow-up circuits, such as the power supply circuitry **108** and/or the load **106**.

[0065] In the conventional construction of FIGS. 6 and 7, the AC line voltage supply angle is θ and the bulk capacitor discharging angle β_{con} is calculated in eq. 1. The capacitance for such a conventional full-bridge rectifier is calculated in equation 2, where P_o is the output power of the rectifier and f_{line} is the AC line frequency.

$$\beta_{con} = \pi - \theta = \pi - \cos^{-1}\left(\frac{V_{bus_min}}{V_{bus_max}}\right) \quad \text{EQUATION 1}$$

$$C_{con} = \frac{-continued}{2P_0\beta_{con}} \quad \text{EQUATION 2}$$

$$C_{con} = \frac{2P_0\beta_{con}}{2^\pi f_{line}(v_{bus_max}^2 - v_{bus_min}^2)}$$

[0066] From equations 1 and 2 for conventional rectifiers, the capacitance is proportional to the angle β_{con} and inversely proportional to AC line supply angle.

[0067] On the other hand, the rectifier **160** in one embodiment according to the present disclosure may enable decreasing the capacitor discharging angle by increasing the AC line supply angle, providing smaller capacitance and capacitor size under the same voltage rating over the conventional construction. In one embodiment, the AC line voltage supply angle may be extended to 2θ due at least in part to the automatic disconnection of the capacitor **110** realized by the charge control circuitry **130** during the second θ so the bulk capacitor discharging angle is reduced to as shown in eq. 3 and the capacitance can be calculated according to eq. 4.

$$C_{con} = \frac{2P_0\beta_{con}}{2^\pi f_{line}(v_{bus_max}^2 - v_{bus_min}^2)} \quad \text{EQUATION 3}$$

$$C_{new} = \frac{2P_0\beta_{new}}{2^\pi f_{line}(v_{bus_max}^2 - v_{bus_min}^2)} \quad \text{EQUATION 4}$$

[0068] As can be seen from eqs. 3 and 4, the capacitance of the bulk capacitor **110** is less than the capacitance for the conventional rectifier circuitry. The ratio η of C_{con} to C can be calculated as follows:

$$\eta = \frac{C_{new}}{C_{con}} = \frac{\pi - 2\theta}{\pi - \theta} \quad \text{EQUATION 5}$$

[0069] The capacitance ratio versus the ratio of the two bus voltage limitations (e.g., V_{bus_max} and V_{bus_min}) is a positive-coefficient relationship. The ratio of the capacitances goes up when the ratio of bus voltage limitations increases, which indicates that more capacitance reduction can be achieved by a larger difference between V_{bus_max} and V_{bus_min} . For instance, as V_{bus_max} approaches or equals the sinusoidal peak of input AC voltage (ignoring voltage drop on the diode-bridge), the lower voltage limit V_{bus_min} may be selected to be close to or at the absolute minimum in order to enhance or maximize the advantage of the capacitance reduction. However, a high bus voltage limitation ratio from the rectifier **160** may undermine the efficiency of the rectifier **160** and a subsequent converter stage (e.g., the power supply circuitry **108**). Therefore, the value of V_{bus_min} may be selected based on a trade-off between capacitor size and overall efficiency for high-density AC-DC converter applications.

[0070] Note that several portions of the analysis described herein may assume full-load conditions. Under light-load condition, the slower slew-rate of capacitor discharging may slightly increase the capacitor discharging angle β in state 4 and potentially shrink line conduction angle θ in state 1. However, the load condition may not substantially affect the operations and component ratings as V_{bus_min} is considered constant.

[0071] The voltages and currents of several components of the rectifier **160** according to one embodiment are summarized in Table I. The bus voltage and the capacitor voltage supplying the load as a function of the instantaneous angle α in a half line cycle are given by eqs. 6 and 7, from which the blocking voltage for the switching circuit **132**, the anti-parallel diode **136**, and the Zener diode **134** can be derived and equal to $V_{bus_max} - V_{bus_min}$. Practically, this blocking voltage may be determined in the range of tens of volts where a wide range of low-voltage selections are available for high performance and low-cost components. The equations of current for the input diode bridge (e.g., rectification circuitry **120**) as i_{BD} , the capacitor **110** as i_{cap} , the anti-parallel diode **136** as i_D , and the switching circuit **132** as i_{SCR} are provided in eqs. 8-11. for each state to evaluate the power loss performance. Based on equations with respect to one embodiment of the present disclosure, a reduction in RMS currents of both the capacitor **110** and the rectification circuitry **120** in the range of bus voltage limitation ratios can be achieved, thereby saving power losses compared with conventional rectifiers. These power loss savings may offset any additional conduction losses on the switching circuit **132** and the anti-parallel diode **136** caused by i_{SCR} and i_D .

[0072] An alternative embodiment of the power supply apparatus is depicted in FIG. 9 and generally designated **200**. The power supply apparatus **200** is similar to the power supply apparatus **100** described in conjunction with FIG. 1, with several exceptions. For instance, the power supply apparatus **200** includes a power source **250**, rectification circuitry **220** with first and second rectification ports **222**, **224**, first and second ports **202**, **204**, and a bulk capacitor **210**, similar respectively to the power source **150**, the rectification circuitry **120**, the first and second ports **102**, **104**, and the bulk capacitor **110**. This circuitry of the power supply apparatus **200**, other than the power source **250**, may form a rectifier **260** that can be coupled to additional power supply circuitry and/or a load. For instance, for purposes of disclosure, a load and power supply circuitry, similar to the load **106** and the power supply circuitry **108**, are absent from the embodiment depicted in FIG. 9. However, it is to be understood that the first and second ports **202**, **204** may be coupled to power supply circuitry and a load similar to load **106** in the power supply circuitry **108** described herein.

[0073] The power supply apparatus **200** in the illustrated embodiment includes charge control circuitry **230** that operates in a manner similar to the charge control circuitry **130**, but incorporating a differently configured switching circuit **232**. The charge control circuitry **230** includes a Zener diode **234** and an antiparallel diode **236**, similar to the Zener diode **134** and the antiparallel diode **136**.

[0074] The switching circuit **232** in the illustrated environment includes an NPN transistor **242** for which an emitter of the NPN transistor **242** is connected to and at least in part forms a cathode terminal of the switching circuit **232**. The switching circuitry **232** may include PNP transistor **244** for which an emitter of the PNP transistor **244** is connected to and at least in part forms an anode terminal of the switching circuit **232**. A collector of the PNP transistor **244** may be connected to a gate of the NPN transistor **242**, and a gate of the PNP transistor **244** may be connected to a collector of the NPN transistor **242**. The switching circuit

232 may include a driving resistor **246** connected between the gate of the NPN transistor **242** and the emitter of the NPN transistor **242**.

[0075] The switching circuit **232** in the illustrated embodiment may replace the SCR of the switching circuitry **132** in FIG. **1** with two back-to-back connected transistors and a driving resistor. This configuration may be less expensive than the SCR-based configuration and may provide additional design freedom.

[0076] A method of producing a rectifier according to the present disclosure is shown in FIG. **10** and generally designated **1000**. The method includes determining the output power and bus voltage limitations based on the power requirements or targeted power density. Step **1002**. The method may also include calculate θ and capacitance according to eqs. 3 and 4, and selecting capacitor **110** with a nearest value of capacitance to the calculation. Step **1004**.

[0077] The method may also include selecting a Zener diode **134**. The reverse breakdown voltage for Zener diode **134** may be substantially equal to the difference of the two bus voltage limitations $V_{bus_max} - V_{bus_min}$. Step **1006**.

[0078] The method may include selecting an SCR or switching circuit **132** or switching circuit **232**. The off-state voltage of the switching circuit **132** and the two transistors (NPN and PNP) in circuit **232** may be larger than the difference of the bus voltage limitations. And the gate current may be smaller than the reverse breakdown current generated by the Zener diode **134**. Step **1008**.

[0079] The method may include selecting an anti-parallel diode **136**. The DC blocking voltage for the anti-parallel diode **136** may be larger than the difference of the bus voltage limitations. Step **1010**.

[0080] Directional terms, such as “vertical,” “horizontal,” “top,” “bottom,” “upper,” “lower,” “inner,” “inwardly,” “outer” and “outwardly,” are used to assist in describing the invention based on the orientation of the embodiments shown in the illustrations. The use of directional terms should not be interpreted to limit the invention to any specific orientation(s).

[0081] The above description is that of current embodiments of the invention. Various alterations and changes can be made without departing from the spirit and broader aspects of the invention as defined in the appended claims, which are to be interpreted in accordance with the principles of patent law including the doctrine of equivalents. This disclosure is presented for illustrative purposes and should not be interpreted as an exhaustive description of all embodiments of the invention or to limit the scope of the claims to the specific elements illustrated or described in connection with these embodiments. For example, and without limitation, any individual element(s) of the described invention may be replaced by alternative elements that provide substantially similar functionality or otherwise provide adequate operation. This includes, for example, presently known alternative elements, such as those that might be currently known to one skilled in the art, and alternative elements that may be developed in the future, such as those that one skilled in the art might, upon development, recognize as an alternative. Further, the disclosed embodiments include a plurality of features that are described in concert and that might cooperatively provide a collection of benefits. The present invention is not limited to only those embodiments that include all of these features or that provide all of the stated benefits, except to the extent otherwise expressly

set forth in the issued claims. Any reference to claim elements in the singular, for example, using the articles “a,” “an,” “the” or “said,” is not to be construed as limiting the element to the singular.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. Self-driven circuitry to be connected in series with a bulk capacitor between first and second output ports of a rectifier, the self-driven circuitry comprising:

a thyristor circuit including an anode terminal, a cathode terminal, and a gate terminal, wherein the anode terminal is connected to a first connector of the bulk capacitor that opposes a second connector of the bulk capacitor that is connected to the second output port, wherein the cathode terminal is connected to the first output port;

a diode connected antiparallel to the thyristor circuit between the anode terminal and the cathode terminal; and

a Zener diode connected parallel to the thyristor circuit between the gate terminal and the anode terminal.

2. The self-driven circuitry of claim 1 wherein the rectifier includes a full diode-bridge.

3. The self-driven circuitry of claim 1 wherein the thyristor circuit includes a silicon-controlled rectifier (SCR), wherein the SCR includes a cathode connected to the cathode terminal, an anode connected to the anode terminal, and a gate connected to the gate terminal.

4. The self-driven circuitry of claim 1 wherein the thyristor circuit includes:

an NPN transistor for which an emitter of the NPN transistor is connected to the cathode terminal;

a PNP transistor for which an emitter of the PNP transistor is connected to the anode terminal, a collector of the PNP transistor being connected to a gate of the NPN transistor, a gate of the PNP transistor being connected to a collector of the NPN transistor; and

a driving resistor connected between the gate of the NPN transistor and the emitter of the NPN transistor.

5. An AC-DC converter comprising:

a rectifier stage operable to output DC voltage, the rectifier stage including:

the rectifier including input ports to be connected to an AC-voltage source, the rectifier including the first and second output ports to deliver output voltage based on power from the AC-voltage voltage,

the bulk capacitor including a first terminal connected to the second output port, and

the self-driven circuitry of claim 1 connected between the first output port and a second terminal of the bulk capacitor that opposes the first terminal of the bulk capacitor,

wherein the AC-DC converter is configured to deliver the DC voltage over a voltage range between a maximum voltage V_{MAX} and a minimum voltage V_{MIN} .

6. The AC-DC converter of claim 5 wherein the rectifier includes a full diode-bridge.

7. The AC-DC converter of claim 5 wherein:

the rectifier stage includes a first stage output and a second stage output;

the cathode terminal of the self-driven circuitry is connected to the first stage output;

the second output port of the rectifier is connected to the second stage output; and

the DC voltage is output from the first and second stage outputs.

8. The AC-DC converter of claim **5** wherein the Zener diode is configured to have a reverse voltage that is substantially equal to the difference VMAX-VMIN.

9. The AC-DC converter of claim **5** wherein an SCR of the thyristor circuit is configured to include an off-state voltage that is larger than the difference VMAX-VMIN, and a gate current ISCR_GATE that is smaller than a reverse break-down current of the Zener diode IZENER_REVERSE.

10. The AC-DC converter of claim **5** wherein the DC blocking voltage of the diode is configured to be larger than the difference VMAX-VMIN.

11. The AC-DC converter of claim **5** wherein a capacitance value of the bulk capacitor substantially corresponds to

$$\frac{2P_o\beta_{new}}{2\pi f_{ine}(V_{MAX}^2 - V_{MIN}^2)}, \text{ where } \beta_{new} = \pi - 2 \cos^{-1}\left(\frac{V_{MIN}}{V_{MAX}}\right),$$

and where f_{ine} is the frequency of the AC-voltage source, and P_o is the output power of the rectifier.

12. The AC-DC converter of claim **5** is a GaN-based active-clamp flyback AC-DC converter for universal serial bus power delivery charger applications.

13. A capacitor charge controller operable to control charge and discharge of a bulk capacitor, the bulk capacitor including a first capacitor terminal and a second capacitor terminal, the capacitor charge controller comprising:

a switching circuit including a first terminal, a second terminal, and an input terminal, wherein the first terminal is operably coupled to a first rectifier output of a rectifier, wherein the second terminal is operably coupled to the first capacitor terminal of the bulk capacitor, wherein the second capacitor terminal of the bulk capacitor is operably coupled to a second rectifier output of the rectifier;

a diode connected in parallel to the switching circuit and including a diode anode terminal and a diode cathode terminal, the diode anode terminal being operably

coupled to the first terminal of the switching circuit, the diode cathode terminal being operably coupled to the second terminal of the switching circuit; and

a Zener diode operably coupled to the input terminal of the switching circuitry and the first capacitor terminal of the bulk capacitor.

14. The capacitor charge controller of claim **13** wherein the switching circuit includes a thyristor with a thyristor anode, a thyristor cathode, and gate input, wherein the thyristor cathode is coupled to the first terminal and the thyristor anode is coupled to the second terminal, wherein the gate input is coupled to the input terminal.

15. The capacitor charge controller of claim **14** wherein the Zener diode controls operation of the thyristor via the gate input.

16. The capacitor charge controller of claim **14** wherein the diode is connected antiparallel to the thyristor.

17. The capacitor charge controller of claim **13** wherein the switching circuit includes:

an NPN transistor for which an emitter of the NPN transistor is connected to the cathode terminal;

a PNP transistor for which an emitter of the PNP transistor is connected to the anode terminal, a collector of the PNP transistor being connected to a gate of the NPN transistor, a gate of the PNP transistor being connected to a collector of the NPN transistor; and

a driving resistor connected between the gate of the NPN transistor and the emitter of the NPN transistor.

18. The capacitor charge controller of claim **14** wherein the capacitor charge controller is self-driven.

19. The capacitor charge controller of claim **13** wherein the capacitor charge controller and the bulk capacitor are provided in series between first and second output ports of a rectifier, wherein the rectifier is operable to receive AC-voltage from an AC power source, and wherein the rectifier, the capacitor charge controller, and the bulk capacitor are operable to output DC-voltage.

20. The capacitor charge controller of claim **19** wherein the Zener diode is configured to have a reverse voltage that is substantially equal to the difference VMAX-VMIN.

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