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(54) **POWER CONVERTER WITH ISOLATED AND REGULATION STAGES**

now Pat. No. 6,222,742, which is a division of application No. 09/012,475, filed on Jan. 23, 1998, now Pat. No. 5,999,417.

(76) Inventors: **Martin F. Schlecht**, Lexington, MA (US); **Richard W. Farrington**, Heath, TX (US)

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Correspondence Address:
HAMILTON, BROOK, SMITH & REYNOLDS, P.C.
530 VIRGINIA ROAD, P.O. BOX 9133
CONCORD, MA 01742-9133

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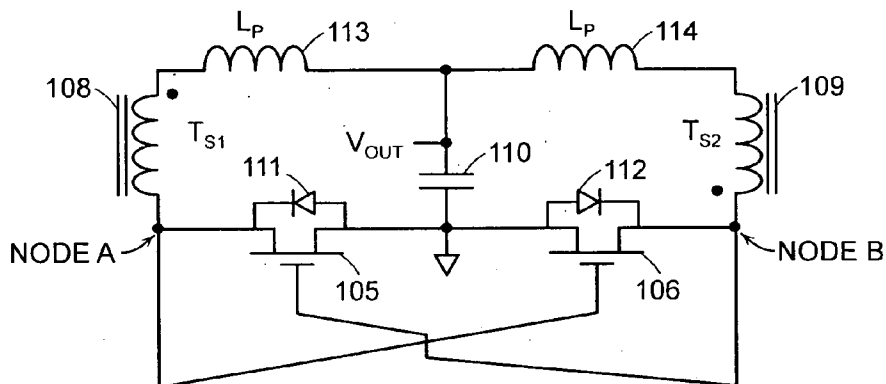
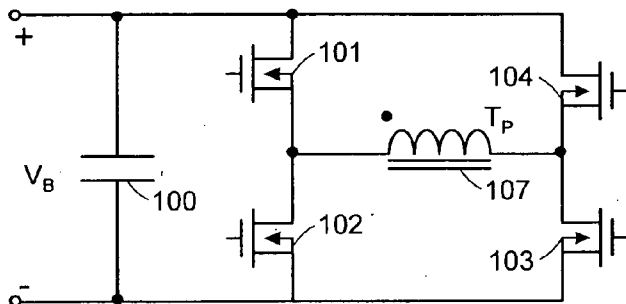
(57) **ABSTRACT**

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In a power converter, the duty cycle of a primary winding circuit causes near continuous flow of power through the primary and secondary winding circuits during normal operation. By providing no regulation during normal operation, a very efficient circuit is obtained with a synchronous rectifier in the secondary operating at all times. However, during certain conditions such as start up or a short-circuit, the duty cycle of the primary may be reduced to cause freewheeling periods. A normally non-regulating isolation stage may be followed by plural non-isolating regulation stages. To simplify the gate drive, the synchronous rectifiers may be allowed to turn off for a portion of the cycle when the duty cycle is reduced. A filter inductance of the secondary winding circuit is sufficient to minimize ripple during normal operation, but allows large ripple when the duty cycle is reduced. By accepting large ripple during other than normal operation, a smaller filter inductance can be used.

Related U.S. Application Data

(60) Continuation of application No. 11/407,699, filed on Apr. 20, 2006, now Pat. No. 7,272,021, which is a continuation-in-part of application No. 10/729,430, filed on Dec. 5, 2003, now Pat. No. 7,050,309, Continuation-in-part of application No. 10/812,314, filed on Mar. 29, 2004, now Pat. No. 7,072,190, which is a continuation of application No. 10/359,457, filed on Feb. 5, 2003, now Pat. No. 6,731,520, which is a continuation of application No. 09/821,655, filed on Mar. 29, 2001, now Pat. No. 6,594,159, which is a division of application No. 09/417,867, filed on Oct. 13, 1999,



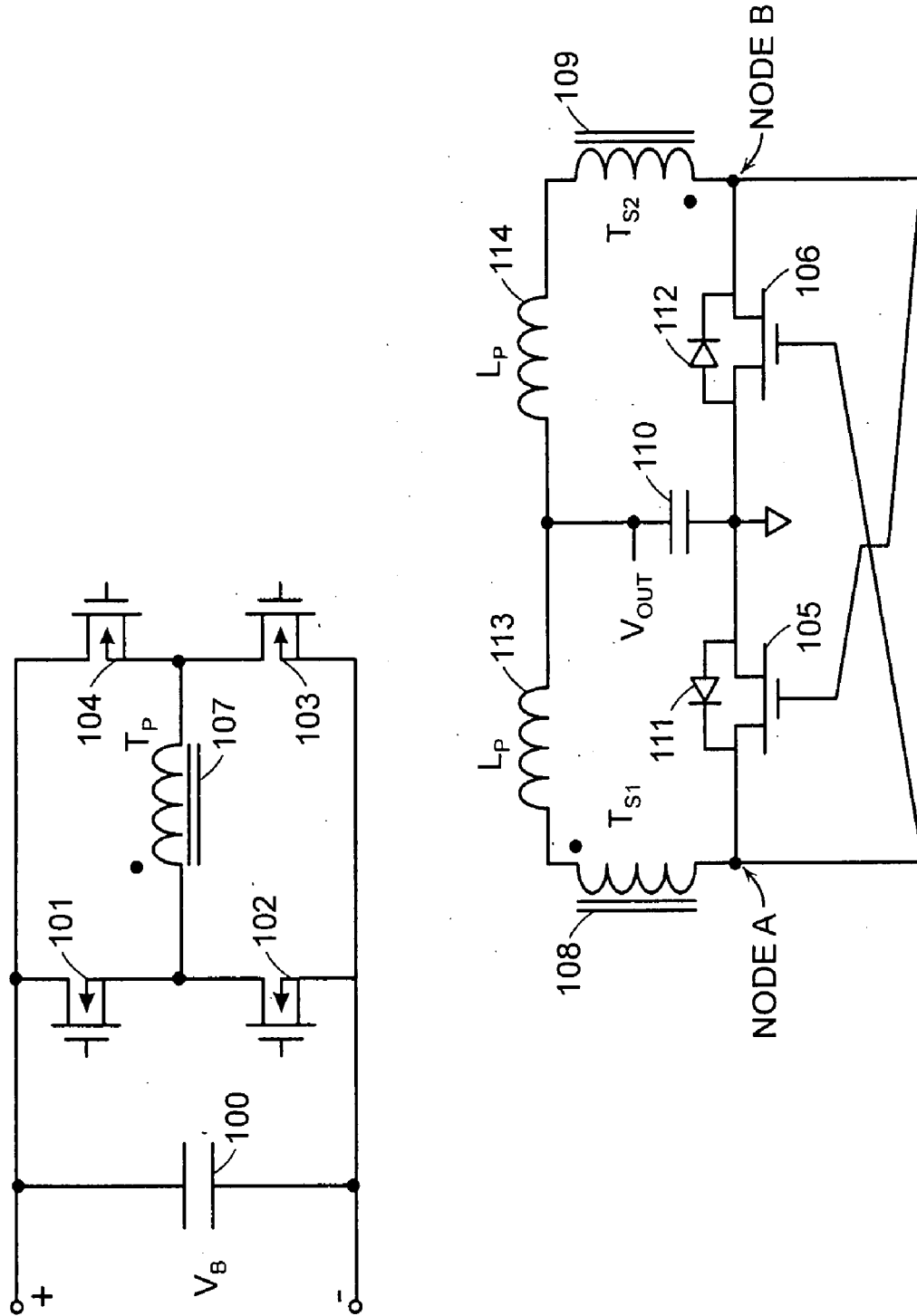


FIG. 1

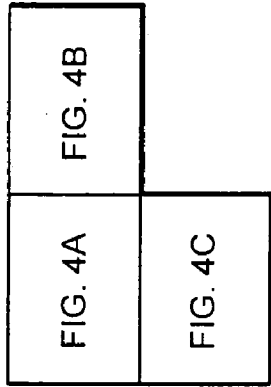


FIG. 4

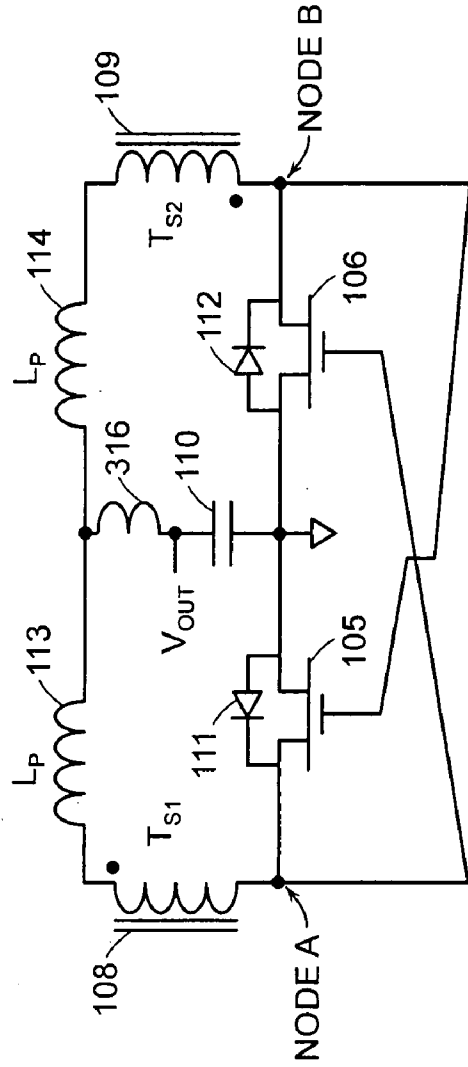
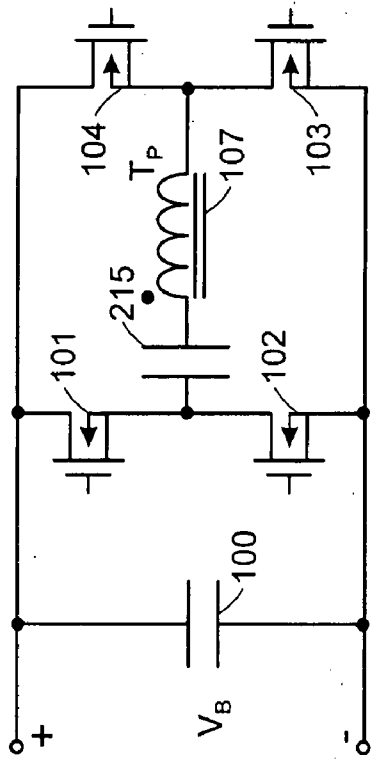


FIG. 3

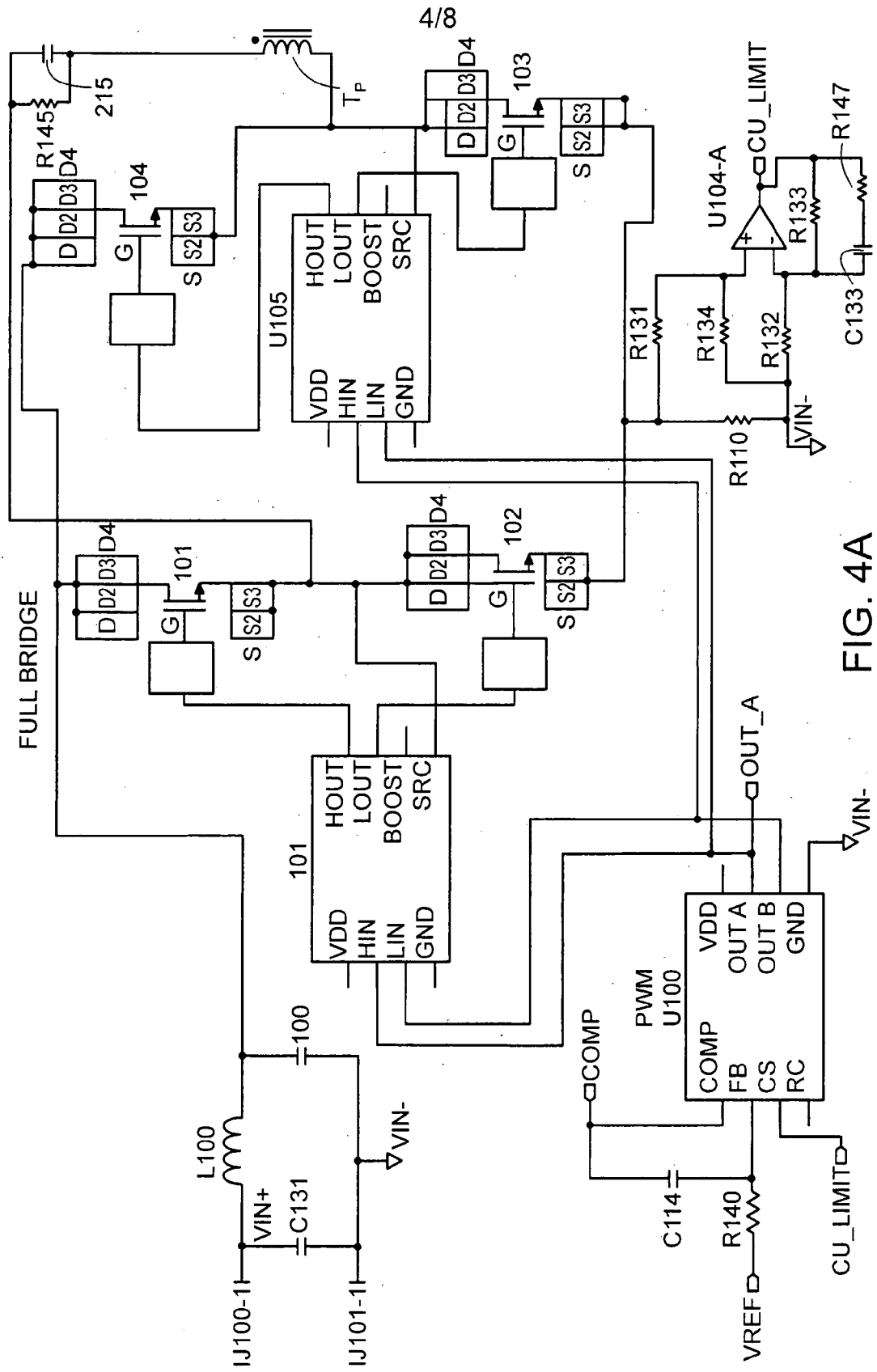


FIG. 4A

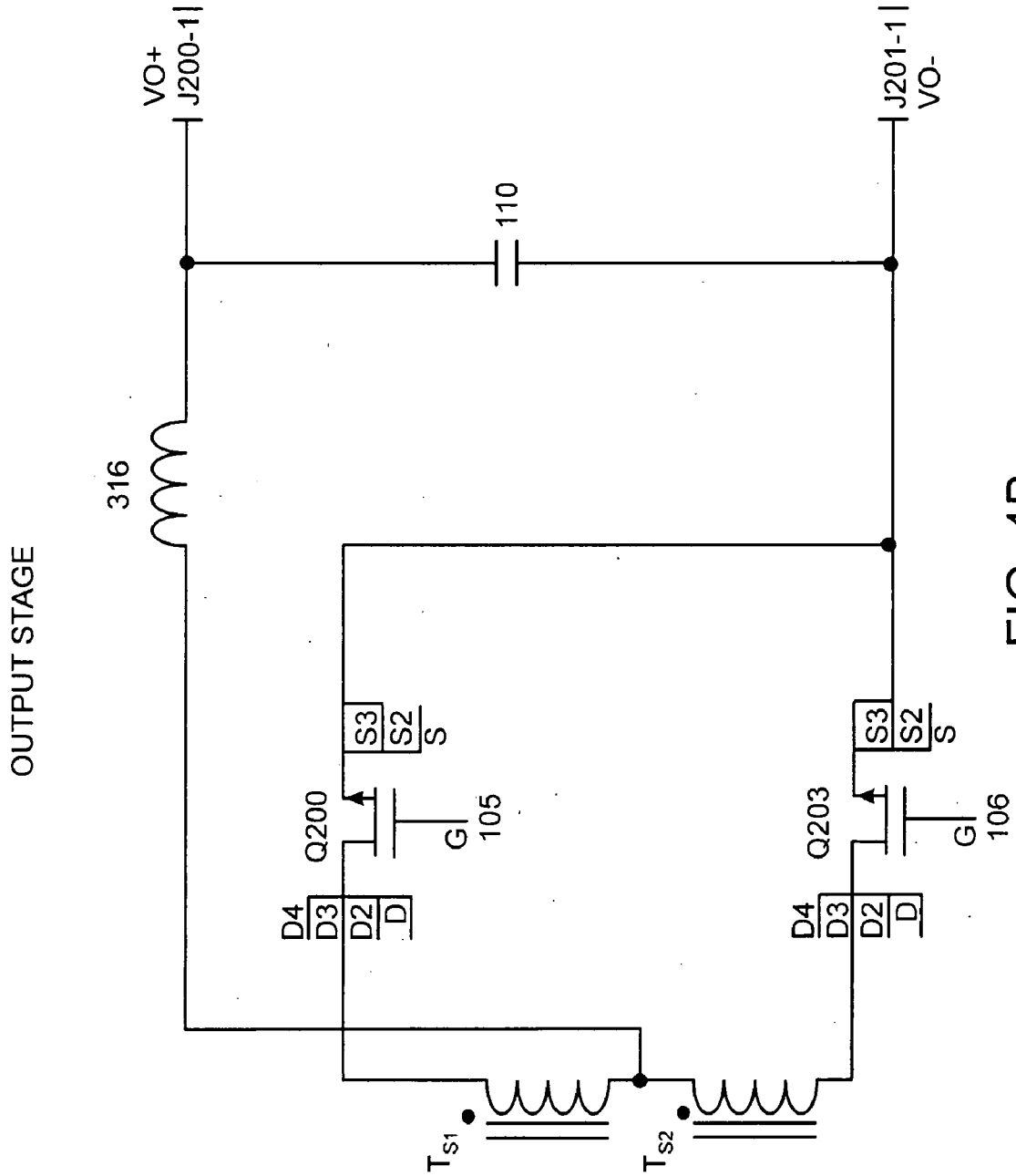


FIG. 4B

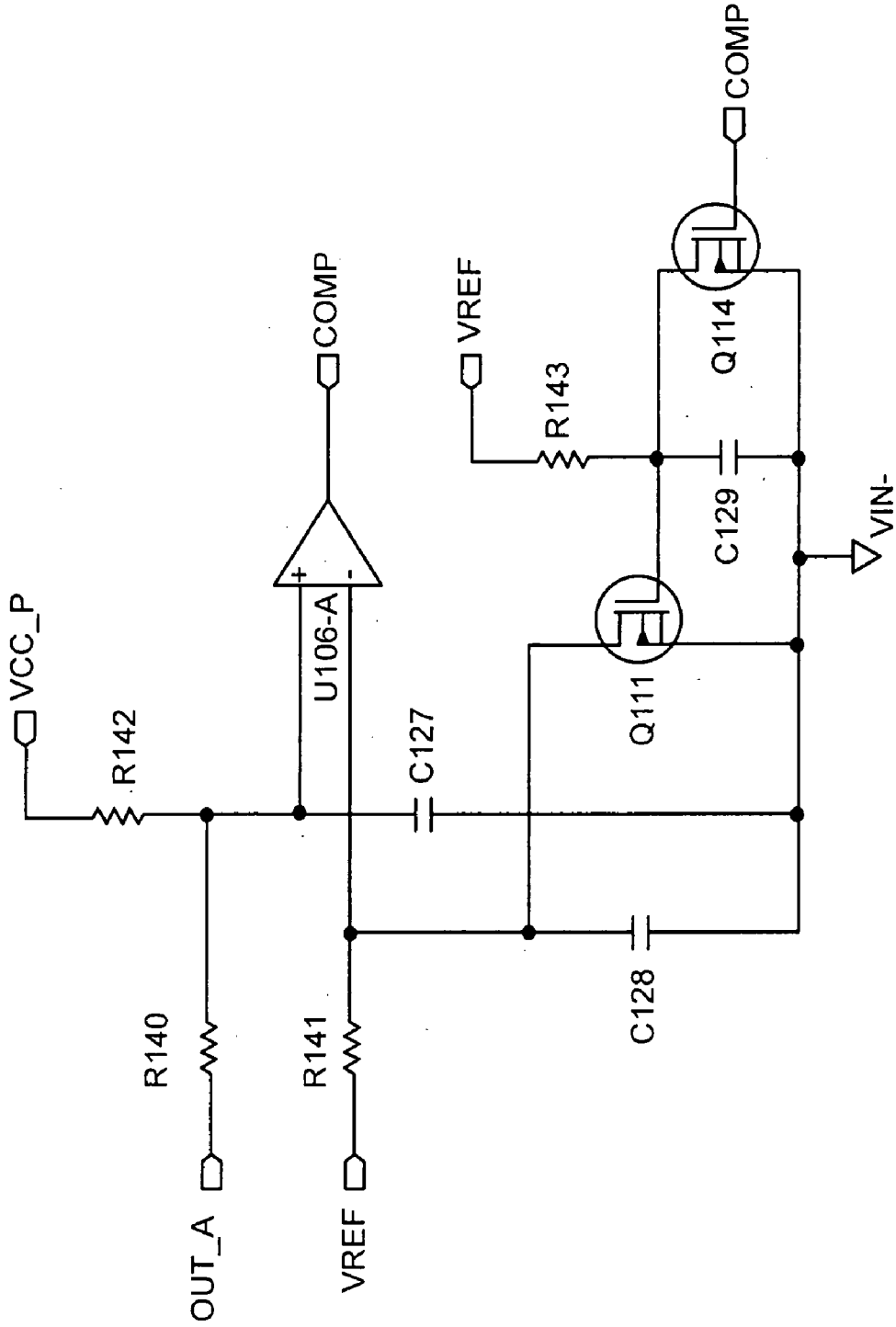


FIG.4C

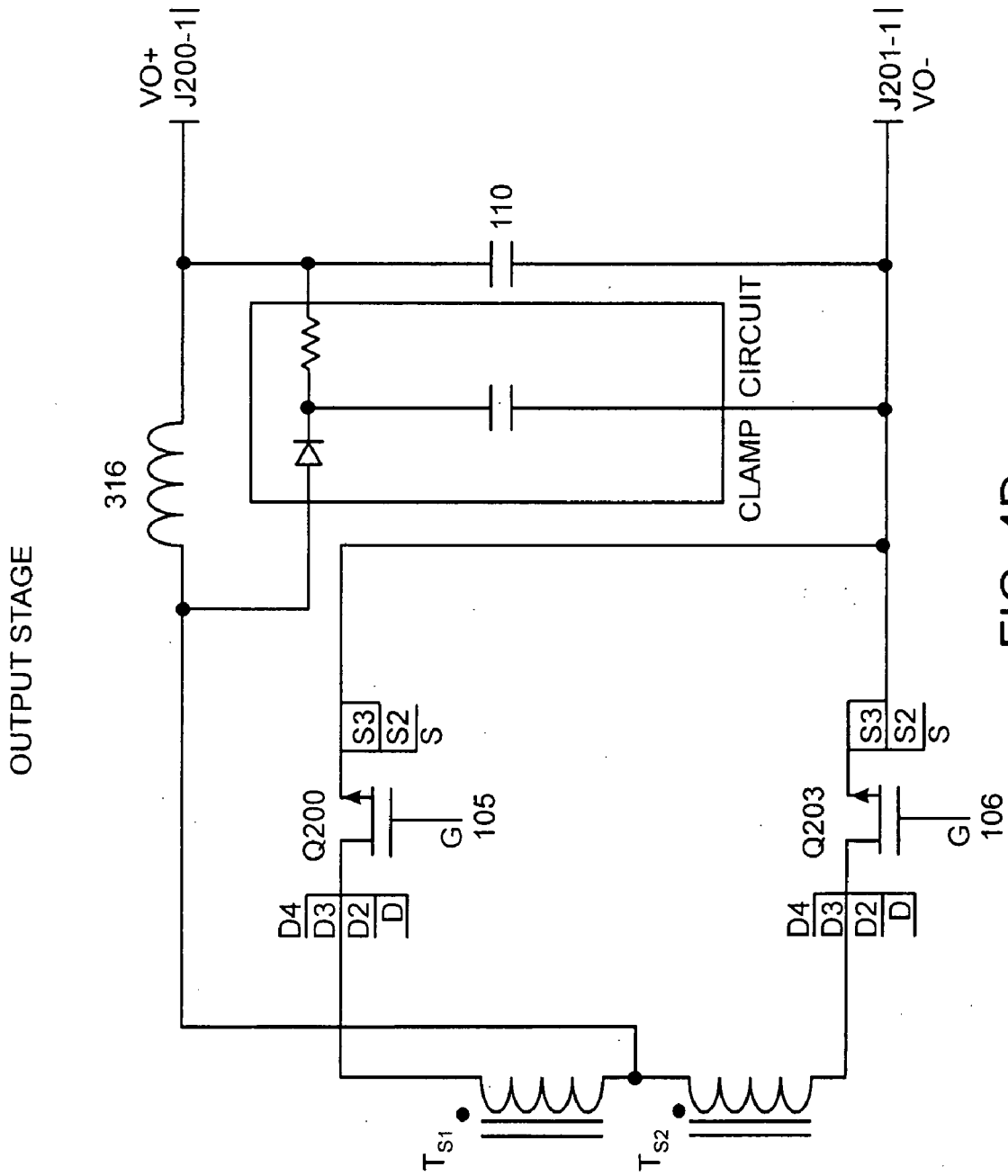


FIG. 4D

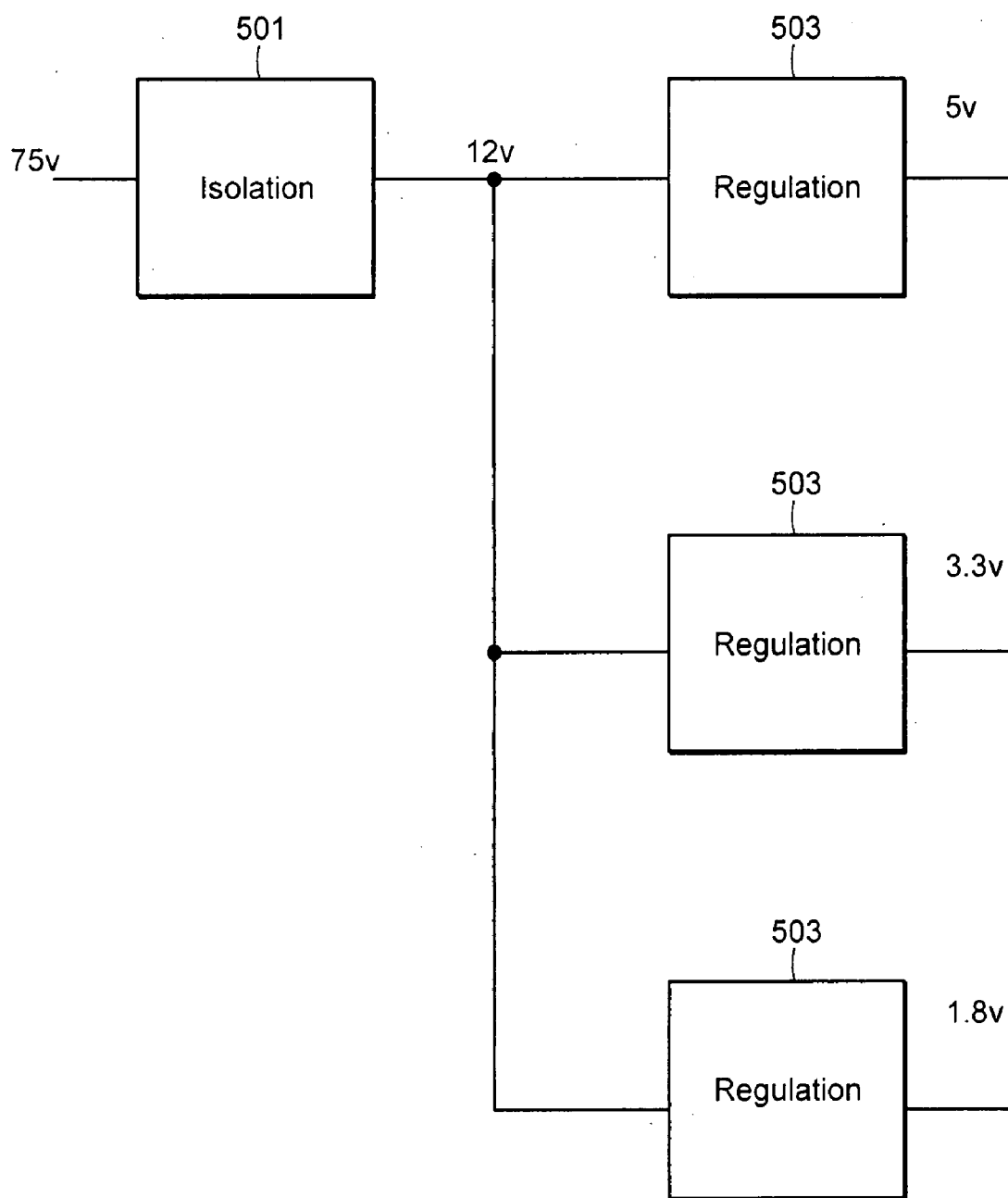


FIG. 5

POWER CONVERTER WITH ISOLATED AND REGULATION STAGES

RELATED APPLICATIONS

[0001] This application is a Continuation of U.S. application Ser. No. 11/407,699, filed Apr. 20, 2006, issuing as U.S. Pat. No. 7,272,021 on Sep. 18, 2007, which is a Continuation-in-Part of U.S. application Ser. No. 10/729,430, filed on Dec. 5, 2003, now U.S. Pat. No. 7,050,309, which claims the benefit of U.S. Provisional Application No. 60/431,673, filed Dec. 6, 2002 and a Continuation-in-Part to U.S. application Ser. No. 10/812,314, filed Mar. 29, 2004, now U.S. Pat. No. 7,072,190, which is a continuation of application Ser. No. 10/359,457, filed Feb. 5, 2003, now U.S. Pat. No. 6,731,520, which is a continuation of application Ser. No. 09/821,655, filed Mar. 29, 2001, now U.S. Pat. No. 6,594,159, which is a divisional of application Ser. No. 09/417,867, filed Oct. 13, 1999, now U.S. Pat. No. 6,222,742, which is a divisional of Ser. No. 09/012,475, filed Jan. 23, 1998, now U.S. Pat. No. 5,999,417, which claims the benefit of U.S. Provisional Application 60/036,245 filed Jan. 24, 1997. The entire teachings of the above applications are incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] This invention pertains to switching power converters. A specific example of a power converter is a DC-DC power supply that draws 100 watts of power from a 48 volt DC source and converts it to a 5 volt DC output to drive logic circuitry. The nominal values and ranges of the input and output voltages, as well as the maximum power handling capability of the converter, depend on the application.

[0003] It is common today for switching power supplies to have a switching frequency of 100 kHz or higher. Such a high switching frequency permits the capacitors, inductors, and transformers in the converter to be physically small. The reduction in the overall volume of the converter that results is desirable to the users of such supplies.

[0004] Another important attribute of a power supply is its efficiency. The higher the efficiency, the less heat that is dissipated within the supply, and the less design effort, volume, weight, and cost that must be devoted to remove this heat. A higher efficiency is therefore also desirable to the users of these supplies.

[0005] A significant fraction of the energy dissipated in a power supply is due to the on-state (or conduction) loss of the diodes used, particularly if the load and/or source voltages are low (e.g. 3.3, 5, or 12 volts). In order to reduce this conduction loss, the diodes are sometimes replaced with transistors whose on-state voltages are much smaller. These transistors, called synchronous rectifiers, are typically power MOSFETs for converters switching in the 100 kHz and higher range.

[0006] The use of transistors as synchronous rectifiers in high switching frequency converters presents several technical challenges. One is the need to provide properly timed drives to the control terminals of these transistors. This task is made more complicated when the converter provides electrical isolation between its input and output because the synchronous rectifier drives are then isolated from the drives of the main, primary side transistors. Another challenge is the need to minimize losses during the switch transitions of the synchronous rectifiers. An important portion of these switching losses is due to the need to charge and discharge the

parasitic capacitances of the transistors, the parasitic inductances of interconnections, and the leakage inductance of transformer windings.

SUMMARY OF THE INVENTION

[0007] In certain embodiments of the invention, a power converter system comprises a normally non-regulating isolation stage and a plurality of non-isolating regulation stages, each receiving the output of the isolation stage and regulating a regulation stage output. The non-regulating isolation stage may comprise a primary winding circuit and a secondary winding circuit coupled to the primary winding circuit. The secondary winding circuit comprises a secondary transformer winding in series with a controlled rectifier having a parallel uncontrolled rectifier. A control circuit controls duty cycle of the primary winding circuit, the duty cycle causing substantially uninterrupted control of power through the primary and secondary winding circuits during normal operation.

[0008] The duty cycle of the primary winding circuit may be reduced to cause freewheeling periods in other than normal operation. Duty cycle might be reduced during the startup or to limit current and may be a function of sensed current.

[0009] The primary winding circuit may include a single primary winding, and the secondary winding circuit may include plural secondary windings coupled to the single primary winding. The primary winding may be in a full bridge circuit having a capacitor in series with the primary winding. In one implementation of the full bridge circuit, during freewheeling, only two top FETs or two bottom FETs are turned off.

[0010] A control signal of the controlled rectifier may be derived from a waveform of the secondary winding circuit. The secondary winding circuit may include a filter inductor and have a capacitor coupled across its output.

[0011] The isolation stage may be a step down stage. For example, it may provide an output of about 12 volts from a DC power source that provides a voltage varying over the range of 36-75 volts. The regulation stages may be down converters to provide outputs of voltage levels to drive logic circuitry. A regulation stage output may, for example, be 5 volts or less, such as 3.3 volts.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

[0013] FIG. 1 shows a full-bridge, single-transformer, voltage-fed isolation stage that incorporates concepts of the '417 patent.

[0014] FIG. 2 illustrates the addition of a capacitor to the primary winding of FIG. 1.

[0015] FIG. 3 illustrates the addition of an output filter inductor to the circuit of FIG. 2.

[0016] FIGS. 4A-4C show a control circuit for the circuits of FIGS. 1-3 and embodying the present invention, and FIG. 4D shows an alternative to the circuit of FIG. 4B.

[0017] FIG. 5 shows an Intermediate Bus Architecture (IBA) implementation of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] A description of preferred embodiments of the invention follows.

[0019] FIG. 1 shows a full-bridge, single-transformer, voltage-fed isolation stage that incorporates synchronous rectification and the concepts of the '417 patent. The operation of this isolation stage is as follows. For the first half of the cycle, MOSFETs 101 and 103 are turned on while MOSFETs 102 and 104 are left off, and the voltage VB is applied positively (according to the "dot" convention) across the transformer's primary winding 107. This voltage, modified by the transformer's turns-ratio, appears across the secondary windings with the appropriate polarity. Power flows into the transformer's primary winding, and out of the first secondary winding 108 to the output. The voltage at Node B is approximately twice the output voltage, and it causes the MOSFET synchronous rectifier 105 to be turned on. The voltage at Node A is therefore slightly below ground, which causes the MOSFET synchronous rectifier 106 to be turned off. These states of the rectifier switches are consistent with the power flowing out of the first secondary winding.

[0020] During the second half of the cycle, MOSFETs 102 and 104 are turned on while MOSFETs 101 and 103 are left off, and the voltage VB is applied negatively across the transformer's primary winding. This negative polarity causes MOSFET 106 to be turned on, MOSFET 105 to be turned off, and power to flow into the primary winding and out of the second secondary winding 109 to the output across capacitor 110.

[0021] The secondary windings are not tightly coupled to each other, as indicated with the parasitic inductances 113 and 114, to achieve the advantages discussed in the '417 patent. A similar setup was shown in the topology of FIG. 9 of the '417 patent since it also used a single transformer.

[0022] Care must be taken in this isolation stage topology to insure that the magnetizing inductance of the transformer does not saturate. One way to do this is to place a large capacitor 215 in series with the primary winding, as shown in FIG. 2. This capacitor will assume a dc voltage across it that counters any imbalance there may be in the positive and negative volt-seconds of the waveforms created by MOSFETs 101-104. Alternatively, several well-known techniques to sense the magnetizing inductor's current could be used to modify the durations of the first and second halves of the cycle.

[0023] The filters at the output of the isolation stages in the '417 patent are composed of one or more capacitive and inductive elements. When the isolation stage is voltage-fed, it may be desirable to have the output filter begin with an inductor 316, as shown in FIG. 3. One benefit this approach provides is that the voltage-fed isolation stages can now be operated with a variable duty cycle control strategy to provide a soft-start capability or to limit current flow in a short-circuit condition. These functions could be provided by the regulation stages in the topologies depicted in the '417 patent, but if the isolation stage is not combined directly with a regulation stage in a single product, then it may be desirable to include these functional capabilities in the isolation stage, as well.

[0024] Under variable duty cycle control, the percentage of the overall cycle (the duty cycle) that MOSFETs 101 and 103 (or MOSFETs 102 and 104) conduct is reduced from the 50%

value described above. For the remaining, freewheeling fraction of the half-cycle, either all of the primary-side MOSFETs are turned off, or at least the two top MOSFETs 101 and 104 or the two bottom MOSFETs 102 and 103 are turned off. During the freewheeling part of the cycle, both diodes 111 and 112 conduct the current flowing through inductor 316, and the voltage across the transformer windings is approximately zero. As is well known, this additional portion of the cycle permits the output voltage to be less than VB divided by the transformer's turns-ratio. How much less depends on the duty cycle. Since during normal operation the isolation stage is operated at a fixed duty cycle in which power is always flowing from input to output (except during the brief switch transitions), the value of inductor 316 can be relatively small to achieve an acceptable output ripple. This reduces the size, cost, and power dissipation of this inductor compared to what it might have been. During those times when the isolation stage is operated under a variable duty cycle, the ripple in the inductor current may then become large, but the larger output voltage ripple that results can usually be tolerated for start-up and short-circuit conditions.

[0025] As mentioned above, during the freewheeling part of the cycle the diodes are carrying the inductor current. This is because the gate drive scheme shown in FIG. 3 would cause the MOSFET synchronous rectifiers to be off during this part of the cycle. The additional power dissipation that occurs due to the higher on-state voltage of the diodes compared to that of the MOSFETs can usually be tolerated for the start-up and short-circuit conditions because they are normally short in duration.

[0026] If the output voltage is high, then it may be desirable to use a capacitive divider technique described in the '417 patent to reduce the voltages applied to the gates of the MOSFET synchronous rectifiers below that of the voltages appearing at Nodes A and B. FIGS. 4A-4C show a circuit schematic of a product based, in part, on the ideas presented here and in the '417 patent. The function of the product is to provide isolation and a transformation of the input voltage to the output voltage according to the turns-ratio of the transformer. It does not, in its normal state of operation, provide regulation. As such it is a very efficient product. One example of its use is to convert a 48V input to a 12V output by using a turns-ratio of 4:1. Since there is no regulation, if the input voltage varies +/-10%, so too will the output voltage vary +/-10%. In certain applications, this variation in the output is acceptable, and well worth the very high efficiency of the converter, which is 96% in this example.

[0027] In addition, since the converter of FIG. 4 does not provide regulation, its output voltage demonstrates a droop characteristic. By this it is meant that for any given input voltage, the output voltage drops slightly as the output current increases. For instance, the output voltage may drop 5% as the output current varies from 0% to 100% of the rated maximum value. This droop characteristic provides automatic current sharing between two or more such converters that might be placed in parallel.

[0028] Note in this schematic that the IC labeled U100 is a pulse width modulator (PWM) control chip that is normally operated such that the gate drive signals that pass through gate drivers U101 and U105 give the fixed duty cycle operation of the full-bridge described above. If the current sensing amplifier U104-A senses that the current flowing on the primary side of the circuit exceeds a threshold value, it commands the PWM control chip to reduce its duty cycle by an amount

determined by how large the current gets above the threshold value. This provides a current limiting scheme for the product that protects against a short-circuit condition.

[0029] Note also that comparator U106-A senses the duty cycle output of the PWM control chip, and compares it to a threshold. If the duty cycle falls below this threshold value, the output of the comparator causes the PWM control IC to shut down. The circuitry around this comparator, including transistors Q111 and Q114, provides a latching mechanism such that the PWM control IC remains off once this condition is observed.

[0030] As described in the '417 patent and illustrated in FIG. 5, in some situations, it may be desirable to place the isolation stage first in the power flow, and to have the regulation stage follow. For example, when there are many outputs sharing the total power, the circuit might be configured as one isolation/step-down (or step-up) stage 501 followed by several DC-DC switching or linear regulators 503.

[0031] The DC power source to the full bridge primary circuit may provide a voltage that varies over the range of 36-75 volts. The output of the isolation stage may be 12 volts, and the regulation stage output may be 5 volts or less. In particular, the regulation stage output may be 3.3 volts. Typically, the regulation stage output is of a voltage level to drive logic circuitry.

[0032] Because the isolation stage uses synchronous rectifiers, it is possible for the current to flow from the output back to the input if, for a given input voltage and duty cycle, the output voltage is too high. This condition might, for example, occur during start-up where the duty cycle is slowly raised from its minimum value to its maximum value, but the output capacitor is already pre-charged to a high voltage, perhaps because it had not fully discharged from a previous on-state condition. It might also occur when the input voltage suddenly decreases while the output voltage remains high due to the capacitors connected to this node.

[0033] The negative current that results could cause destructive behavior in the converter or in the system if it is not kept small enough.

[0034] One way to avoid this condition is to turn off either just the top two primary-side MOSFETs 101 and 104, or just the bottom two primary-side MOSFETs 102 and 103, during the freewheeling period, as described above. By leaving the other two primary-side MOSFETs on, the voltage across the primary and secondary windings of the transformer is guaranteed to be essentially zero during the freewheeling period. Given the gate drive scheme shown in FIG. 3, this, in turn, ensures the controlled rectifiers will be off during this part of the cycle.

[0035] With the controlled rectifiers off, negative current cannot flow during the freewheeling period. Negative current can flow during the non-freewheeling part of the cycle, but since it must always start at zero, its value is limited to the ripple that the inductor permits, which is typically small enough to not cause a problem. This negative current will be reset to zero at the start of each freewheeling period, either by

providing a clamp circuit, as shown in FIG. 4D, or by allowing the controlled rectifiers to avalanche and act as their own clamp. Since the clamp circuit must only work for a short duration, it need not recover its absorbed energy and so can be simple, such as the one shown in FIG. 4D.

[0036] To limit the negative current, the isolation stage could operate in a reduced duty-cycle mode. While the control circuit is typically designed to achieve this mode during start-up and shutdown of the isolation stage, it is not the normal mode of operation. If, during normal operation, the input voltage drops suddenly, a large negative current can flow because there are no freewheeling periods.

[0037] To avoid this condition, the current flowing through the converter can be sensed, either by sensing the load current directly, or by sensing a signal indicative of the load current. When the load current falls below some threshold, the duty cycle of the isolation stage can be reduced from its maximum value to provide freewheeling periods. Given the drive scheme for the primary-side MOSFETs outlined above, the negative current will then be kept small since the controlled rectifiers will be turned off for a portion of the cycle.

[0038] While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims. For example, whereas the Figures show the secondary side rectification circuit arranged in a center tapped configuration with two secondary windings and two synchronous rectifiers, as is well known it could be a full wave rectification configuration. One could use a full-bridge rectification circuit in which there is only one secondary winding and four synchronous rectifiers. Such a circuit reduces voltage stress on the synchronous rectifiers when they are off by a factor of two during normal operation of the converter.

What is claimed is:

- 1. A power converter system comprising:
 - a normally non-regulating isolation stage comprising:
 - a primary winding circuit;
 - a secondary winding circuit coupled to the primary winding circuit, the secondary winding circuit comprising a secondary transformer winding in series with a controlled rectifier having a parallel uncontrolled rectifier; and
 - a control circuit which controls duty cycle of the primary winding circuit, the duty cycle causing substantially uninterrupted flow of power through the primary and secondary winding circuits during normal operation; and
 - a plurality of non-isolating regulation stages, each receiving the output of the isolation stage and regulating a regulation stage output.
- 2-48. (canceled)

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