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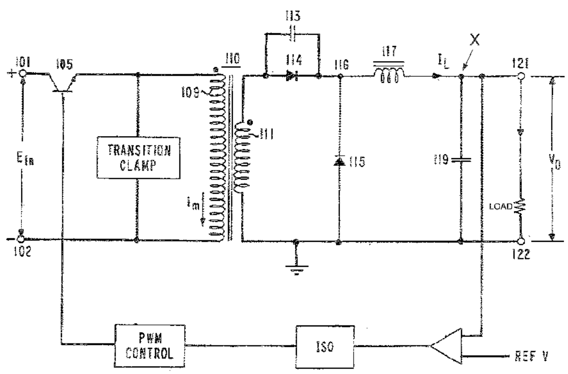


Figure 1

(57) **Abstract:** This invention relates to method s and apparatus for regulating the output voltage and/or current of switch mode power converter, in particular forward converters. A method of regulating the output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output; and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output and a secondary side rectifier; the method comprising: sensing a voltage on said primary winding or on an auxiliary winding of said transformer during a period when said switch is of f and said secondary side rectifier is conducting; and controlling a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

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# Forward Power Converters

## FIELD OF THE INVENTION

This invention relates to methods and apparatus for regulating the output voltage and/or current of switch mode power converter, in particular forward converters.

## BACKGROUND TO THE INVENTION

Figure 1 (which is taken from US 4,688,160) shows an example of a forward power converter comprising a dc input 101, 102 coupled to the primary winding 109 of a transformer 110. The primary winding 109 is connected in series with a switching device 105, here a bipolar transistor, which switches on and off, during an on period building up magnetising flux in the primary winding 109, which drives a current in a secondary winding 111 of the transformer. Unlike a so-called flyback converter, in a forward converter the primary and secondary windings have matched polarities, as indicated by the dots on the windings in Figure 1. The output from the transformer 110 is rectified by a rectifier 114 and smoothed by a smoothing capacitor 119 to provide a dc output 121, 122. When switch 105 is off the core of the transformer is "reset" allowing the magnetising flux to return to its initial state. In the example of Figure 1 (US 4,688,160) this is performed by resonant action between the magnetising inductance of transformer 110 and a capacitor 113 shunting diode 114.

The circuit of Figure 1 includes a large output choke 117 between rectifier 114 and smoothing capacitor 119, and a freewheeling or "flyback" diode 115 across the series combination of choke 117 and smoothing capacitor 119. This is because when the switch 105 is turned off, because the primary and secondary windings have the same sense, rectifier 114 immediately becomes non-conducting. The function of the freewheeling diode 115 is to allow the choke 117 to maintain a continuous output current into output node "X" when switch 105 is off by providing a path for this current.

Figure 1 shows a conventional, continuous forward converter. There are many other prior art documents describing similar converters, including, for example, US 4,415,959; US 6,760,236; US 6,304,463; US 6,252,781; US 4,788, 634; EP0 074 399; US 2005/0270809 (WO 2004/057745); and the reference design SLUA276 for the Texas Instruments UCC38C42.

Switch power converters are used to transfer power from a voltage source (usually DC, or rectified AC) to a load, usually as DC power. The power converter would preferably provide the following functions: conversion from one voltage to another voltage, galvanic isolation between the power source and the load, regulation of the output voltage, and limiting of the output current in overload situations. Not all of these functions may be incorporated in any given design but these are particularly desirable features for off-line AC (mains powered) converters.

There are many different topologies for power converters, including forward, fly-back, buck, and boost converters and their variants, refinements and derivatives. In the field of low-power off-line AC/DC converters a fly-back topology is often used. Forward converters, though potentially less expensive, are more difficult to control in particular to regulate output voltage or current. This is complicated in off-line converters because of the desirability of an isolation barrier between the (mains) input side and the output side: Regulation may be performed by sensing a secondary voltage or current and communicating deviations (error signals) to a primary switching control circuit via an optocoupler or an additional signal transformer, but this adds significantly to the cost of manufacture and causes difficulties associated with achieving sufficient isolation for safety.

Background prior art can be found in US 3,517,300, US 2007/024255, US 5,400,239, US 5,519,599, US 5,631,810, US 6,760,235, EP0 987 815A, EP1 513 248A, US6,459,594, WO2006/080112, and US2003/0035306.

We have previously described, in GB 0706246.6 filed 30 March 2007 and US 11/732108 filed 2 April 2007, both hereby incorporated by reference in their entirety, techniques to stabilise the power output of a forward converter against variations in the load applied. However there remains a need for improved regulation techniques and, in particular, techniques to regulate the output voltage and/or current against variations of the incoming (primary-side) supply. It would be further desirable to provide voltage and/or current regulation techniques which did not need to employ an optocoupler or an additional signal transformer to transfer error signals from the secondary side to a primary side of the power converter, especially for off-line converters.

## SUMMARY OF THE INVENTION

According to a first aspect of the invention there is therefore provided a method of regulating the output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer, and wherein said transformer includes an auxiliary winding; the method comprising: sensing a voltage on said auxiliary winding of said transformer during a period when said switch is on to sense said output voltage; and controlling a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

Preferred embodiments of the forward converter comprise off-line (mains powered) power converters but embodiments of the techniques may also be employed in dc-to-dc converters where input-output isolation may not be required and thus, for example, in embodiments the transformer may be an auto transformer. Embodiments of the technique are, however, particularly advantageous for off-line power converters where isolation between the input side and the output side of the power converter is important for safety reasons. Thus in preferred embodiments of the method the sensing and controlling are both performed on a primary side of the forward converter. In embodiments the sensing may be performed without rectifying the sensed voltage – a rectifier is not necessary.

The voltage sensed on the auxiliary winding of the transformer is, in general, not a perfect reflection of the secondary side (output) voltage due to voltage drop in the secondary side circuitry of the power converter and, more generally, also to losses in the transformer (which may be modelled as a secondary side impedance which includes transformer properties). Thus preferred embodiments of the method further comprise compensating for a change in a value of the sensed auxiliary winding voltage relative to the output voltage due to loading of the power output: in general because of the voltage drop in the secondary side circuitry (and other losses) the output voltage will fall more than the auxiliary winding voltage thus resulting in a differential change between the two on loading.

In preferred embodiments this compensating is performed by adjusting a value derived from the sensed voltage, for example to give a scaled value of the sensed voltage, irresponsive to a current through the switch when the switch is on. Thus, broadly speaking, preferred embodiments of the method look at the primary side supply to predict or estimate the losses in the secondary side and hence the compensation to be applied to the sensed auxiliary voltage in order to obtain a more accurate measure of the actual power converter output voltage. Conveniently this compensating may be performed by coupling a signal dependent on this current into a potential divider coupled to the auxiliary winding. Thus the scaled sensed voltage may be adjusted by injecting current into a node of the potential divider at which this scaled voltage is present, for example by coupling this node to a (primary side) current sense node of the power converter, for example via a resistor.

In general the power converter will include control circuitry for controlling the switching device and a power supply for this control circuitry may be derived from the auxiliary winding of the transformer. In embodiments of the method the sensing of the auxiliary winding voltage may be performed by sensing a power supply current to this control circuitry via a resistance. In embodiments this may provide a sufficiently accurate estimate of the auxiliary winding voltage and has the advantage that a power supply controller integrated circuit, in embodiments, therefore has no need of an additional voltage sensing pin.

The skilled person will understand that the controlling of the proportion of time for which the switch is on may employ a variety of pulse duration control techniques; potentially even pulse amplitude modulation may be employed. Conveniently, however, a duty cycle of the switching is controlled to control the output voltage of the power converter.

In preferred embodiments the power converter comprises a resonant discontinuous forward converter (RDFC).

In a related aspect the invention provides a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer, and wherein said transformer includes an auxiliary winding, and wherein said power converter further comprises a voltage sense circuit to sense a voltage on said auxiliary winding of said transformer during a period when said switch is on to sense said output voltage; and a control circuit to control a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

The skilled person will appreciate that the sensing and control circuitry may be either analogue or digital.

In another aspect the invention provides a method of regulating the output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output; and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output and a secondary side rectifier; the method comprising: sensing a voltage on said primary winding or on an auxiliary winding of said transformer during a period when said switch is off and said secondary side rectifier is conducting; and controlling a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

In embodiments the sensing of the voltage on the primary or auxiliary winding may be performed either directly or indirectly (in the latter case, for example, by sensing a current).

Preferably the power converter comprises a resonant discontinuous forward converter such that the sensed voltage is substantially resonant. Preferably then the sensing comprises sensing adjacent an end of a resonant cycle of this substantially resonant voltage. Broadly speaking in embodiments when the switch is turned off the sensed voltage rises and then falls towards to the end of the resonant cycle and as the voltage falls a point is reach at which the secondary side rectifier begins conducting. In preferred embodiments the voltage is sensed adjacent this point; this is advantageous because at this point in the cycle the current in the secondary side rectifier is low and thus the output voltage drop across this rectifier is predictable. Embodiments of the method thus further comprise compensating for this output voltage drop when controlling the output voltage of a power converter.

In some preferred embodiments therefore, the sensing senses a voltage on the auxiliary winding via a second rectifier, which effectively adjusts for the drop across the secondary side rectifier. It is desirable to have a relatively low current through this second rectifier so that there is relatively little voltage drop across this rectifier. However in embodiments it is also desirable to derive a power supply for control circuitry for controlling the switch from an auxiliary winding on the transformer. Thus in embodiments a third rectifier is employed to derive this (low voltage) power supply for the control circuitry, in order not to draw too much current through the second, voltage sensing rectifier. Thus preferably the second, voltage sensing rectifier is not used to derive a power supply for the control circuitry. In other embodiments a second auxiliary winding is provided on the transformer and this second auxiliary winding is used to provide a power supply for the control circuitry, the first auxiliary winding being used for the voltage sensing. Optionally these two auxiliary windings may be combined in a single physical winding with a tap. In some preferred implementations these two auxiliary windings have matched numbers of turns and construction (and optionally, matched to the secondary), again to increase the accuracy of the voltage sensing.

In embodiments an auxiliary supply is employed for driving the switch on; for example in the case of a bipolar transistor switching device this auxiliary supply may be employed to provide base current to the bipolar transistor during the on-period. In our co-pending UK Patent Application No. 0708196.1 filed 27 April 2007 (and corresponding foreign applications claiming priority from this), hereby incorporated by reference in its entirety, we describe some particularly advantageous techniques for driving bipolar switching devices such as a bipolar junction transistor (BJT) or insulated gate bipolar transistor (IGBT), in particular to control the degree of saturation when the device is on and hence improve turn-off time. These techniques may advantageously be employed in embodiments of the invention. The afore-mentioned auxiliary supply may be employed to provide power for such a base or gate drive.

At times when the switch is off there may be substantially no current to the control terminal of the switch and hence at these times a circuit node providing the auxiliary supply may instead be employed for voltage sensing. This has the advantage of reducing the number of external connections such as pins in a forward switch mode power converter controller integrated circuit configured to implement an embodiment of the above-described method.

In a related method the invention provides a controller for controlling an output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer and a secondary side rectifier; the controller comprising: a circuit to sense a voltage on said primary winding or on an auxiliary winding of said transformer during a period when said switch is off and said secondary side rectifier is conducting; and a circuit to control a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

As previously mentioned, in embodiments of the above-described techniques implemented in a controller integrated circuit (IC) a single pin may be used for both a power supply and for voltage sensing.

Thus in a further aspect the invention provides a controller integrated circuit (IC) for controlling an output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer and a secondary side rectifier; said controller IC including a sensing circuit to sense a voltage on said primary winding or on an auxiliary winding of said transformer, a control circuit to control proportion of time for which said switch is on, responsive to said sensing, to control said output voltage, and a switch drive circuit to provide a drive to said switch to turn said switch on; wherein said controller IC has a plurality of external connections; and wherein one of said external connections comprises a multi-functional connection to provide a voltage sense input to said sensing circuit and to provide power for powering said switch drive circuit, both to enable sensing of said voltage and to provide power for said drive to said switch.

In embodiments a single connection is used for voltage sensing and either supply to the control circuit or supply to drive the switch. In some embodiments, as described above, the voltage sensing circuit is configured to sense a voltage on the auxiliary winding by sensing a power supply current provided via the multi-functional connection. In other embodiments, again as described above, the controller IC is configured to use the multi-functional connection at different times to sense the primary or auxiliary winding voltage and to provide power to drive the switch, more particularly using the multi-functional connection to drive the switch when the switch is on and using the multi-functional connection to sense the primary/auxiliary winding voltage when the switch is off. Thus in some embodiments the single pin may be a power supply pin and the sensing may be performed by sensing a power supply current, and in other embodiments the pin may be multiplexed and used to provide a drive (current) for a primary-side switch during an on period of the switch and for sensing during a period when the switch if off.

**Output Inductance**

In general embodiments of the forward power converters we describe regulate by down-regulation, that is they generate a higher secondary side voltage than required and then reduce this as needed. This results in a mismatch between the secondary winding voltage and the output voltage, the larger the degree of regulation desired (for example due to a varying mains/line voltage input) the larger the potential degree of mismatch). This problem can be addressed by including an output inductor between the secondary winding and the power output of the forward converter; this inductance (in addition to leakage inductance of the transformer) between the power source and the load facilitates a degree of voltage mismatch and may be considered, using a mechanical analogy, as a form of "spring". A large inductor would be preferable because this can store larger amounts of energy but a problem can arise when the primary-side switch turns off, in particular when a significant current is flowing through the series (output) inductance (which may include the transformer leakage inductance). In such circumstances there can be a very fast rise of the switch voltage on the primary side, potentially to destructive levels. A further difficulty is that it is desirable, for efficiency, to be able to operate the forward power converter in a resonant mode but with a large series output inductance resonance can occur on this rather than on the primary side of the transformer inductance as desired and, for example, the secondary side current may not fall to zero even at the end of the off period of the switch, in which case resonance on the primary side may be lost together with the benefits of resonant switching.

We will therefore describe a technique in which capacitance ($C_z$) is added in parallel across the power output of the forward converter, on the secondary winding side of the series output inductance.

According to a further aspect of the invention there is therefore provided a method of regulating the output voltage of a resonant forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer via said secondary winding and a rectifier coupled to said secondary winding to transfer power to said power output, the method comprising coupling an inductor in series between said secondary winding of said transformer and said power output, and operating said power converter such that a voltage on said secondary winding is substantially resonant during an off period of said switch; the method further comprising coupling a first, smoothing capacitor in parallel across said power output on an output side of said inductor and coupling a second capacitor in parallel across a combination of said secondary winding and said rectifier on a secondary winding side of said inductor, and regulating an output voltage of said power supply by varying an on period of said switch such that a consequent variation in a voltage on said second capacitor filtered by said inductor and said smoothing capacitor varies an average value of said output voltage of said power converter.

Thus in embodiments the voltage on the second capacitor is filtered by the inductor and the smoothing capacitor to provide an average value of the second capacitor voltage at the output of said power converter. Preferably the forward power converter is a resonant discontinuous forward converter, and preferably, therefore, a current through the secondary winding has fallen to substantially zero by the end of the off period of the switch.

In embodiments if the afore-mentioned capacitance ($C_z$) is too large because there may be only a small (transformer) leakage inductance the voltage on this capacitance may stay approximately constant and thus regulation action can be substantially diminished (because, broadly speaking, the voltage on this capacitance is approximately constant at the primary voltage transformed by the turns ratio). However if the value of the capacitance ($C_Z$) is reduced then varying the mark:space ratio of the cyclical primary-side switching can vary the voltage on this capacitance and hence facilitate regulation. Whilst more particularly if the value of this capacitance is small then the voltage on the capacitance rises and falls, rising when the switch is on and falling when the switch is off. The mean value of the voltage across this capacitor depends on the duty cycle of the switch and more particularly on the on period of the switch (since in a resonant converter the off period may be substantially constant). Thus by varying the on period of the switch the average voltage across this capacitance can be varied and the series output inductance and output smoothing capacitor can be employed to, in effect, extract the mean value of this voltage, thus providing an opportunity to regulate the voltage output of the power supply by varying the proportion of time for which the switch is on, for example by varying the mark:space ratio of a switching waveform driving switch.

Thus in a related aspect the invention provides a resonant forward switch mode power converter with a controllable output voltage, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output, the converter further comprising: a rectifier and an inductor in series between said secondary winding of said transformer and said power output; a first, smoothing capacitor coupled in parallel across said power output on an output side of said inductor; and a second capacitor coupled in parallel across a combination of said secondary winding and said rectifier on a secondary winding side of said inductor; and a controller to vary an on period of said switch; and wherein said second capacitor has a value which is sufficiently small that, in operation, a peak-to-peak value of an ac component of a voltage across said second capacitor due to said cyclical switching is at least 10% of an average DC voltage across said second capacitor, and wherein an impedance of said inductor at an operating frequency of said power converter is greater than an impedance of said second capacitor at said operating frequency such that, in operation, variation of said on period of said switch by said controller varies an average value of said output voltage of said power converter.

In embodiments the ac component of the voltage across the second capacitor may be at least 20%, 30% or 50% of the average DC voltage on the capacitor. This may be measured at a predetermined output loading, for example a loading of 50% of the peak secondary EMF (primary supply voltage factored by the turns ratio of the transformer). In embodiments the current in the secondary winding may be discontinuous but the current in the series output inductance may not be. Thus in embodiments the current through the series output inductance may or may not fall to zero but in some preferred embodiments the current through the secondary winding does fall to zero, that is the forward converter is configured to operate in a discontinuous mode. As mentioned above, preferably the impedance of the series output inductor is greater than the impedance of the second capacitor at an operating frequency of the power supply; this frequency may be in the range 20 KHz to 200 KHz, 500 KHz or 1 MHz.

## Secondary side techniques

As described above, a series inductance on the secondary side of a forward power converter may be employed to facilitate regulation of the output current or voltage of such a converter, more particularly by varying the on:off duty cycle of the primary switch. The output voltage may be sensed by circuits on the secondary side and a power control signal is passed to the primary side to effect control of power delivery. In this case, however, problems can arise in controlling the switch, particularly in off-line (mains powered) converters where isolation between the primary and secondary sides of the converter is important for safety reasons. However the inventors have recognised that power delivery can further be controlled by a switch inserted in the secondary circuit.

According to a further aspect of the invention there is therefore provided a method of regulating the output current or voltage of a forward switch mode power converter, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer with matched polarity windings coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer; to transfer power to said power output via said secondary winding of said transformer, the method comprising: providing a secondary side controllable switch in series between said secondary winding and said power output; sensing, on said secondary side of said forward switch mode power converter, a signal dependent on said output current or voltage of said power converter; and controlling an on-off switching of said secondary side controllable switch responsive to said sensing of said signal dependent on said output current or voltage, to control a proportion of said power cyclically switched by said primary-side switch transferred to said power output to thereby regulate said output voltage or current.

In some preferred implementations of the method the secondary-side switch is on substantially only at times when the primary-side switch is on. In some preferred embodiments switching of the secondary side switch is at least partially synchronised with switching of the primary side switch; for example one or both of the switching on and switching off times may be substantially synchronised (where both are synchronised the secondary side switch passing or blocking whole/integral primary side switching cycles).

In some embodiments the method includes sensing, on the secondary side of the power converter, a timing of the cyclical switching of the primary-side switch, and then controlling the timing of the secondary-side switch relative to the timing of the primary-side switch to vary the power delivered and hence regulate the output current or voltage of the power converter. This varying of the timing may comprise one or both of delaying a turn-on and advancing a turn-off of the secondary side switch relative to the primary side switch. In the latter case the method may include estimating a turn-off time of the primary-side switch in advance of a present cycle, using timing measured from a previous cycle. This is particularly effective in a resonant converter since in such an arrangement the off-time of the primary-side switch may be approximately constant.

In other embodiments the secondary-side switch may comprise a thyristor (or triac), the on-off switching of the thyristor/triac being controlled by a gate voltage or current. More particularly in embodiments the gate may be arranged so that the thyristor/triac automatically switches on at the start of each cycle (more particularly when the primary side switch switches on) unless the gate is controlled to prevent the thyristor/triac from firing. In accordance with thyristor/triac operation, the thyristor/triac will automatically turn off when the secondary current reduces to zero, which is typically shortly after the primary side switch switches off. The gate may be controlled from an output voltage or current sensing circuit for example by comparing the output condition(s) to a reference level(s).

In this way in embodiments of the method the secondary-side switch is controlled to either couple through or block complete cycles of power transfer to the output of the converter to thereby regulate the output voltage or current. If the output is too high one or more complete cycles may be blocked, thus down-regulating from the input power. Using a thyristor/triac provides a particularly convenient and cost-effective implementation of such an arrangement.

In some preferred embodiments the method further comprises providing an inductor coupled in series with the secondary-side switch. This may be employed to reduce a rate of rise of a current through the secondary-side switch due to a mismatch between voltage on the secondary winding and a voltage at the output of the forward converter.

The invention also provides a forward power converter including means to implement the above-described method and the described embodiments thereof.

Thus in a related aspect the invention provides a forward switch mode power converter with output regulation, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer with matched polarity windings coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer; said power converter further comprising: a secondary side controllable switch coupled in series between said secondary winding and said power output; a sensing circuit, on said secondary side of said forward switch mode power converter, to sense a signal dependent on an output current or voltage of said power converter; and a secondary side control circuit coupled to said sensing circuit and to said secondary side controllable switch to control an on-off switching of said secondary side controllable switch responsive to said sensed signal dependent on said output voltage or current to thereby regulate said output voltage or current.

Thus in a further related aspect the invention provides a method of regulating the output current or voltage of a switch mode power converter, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer; the method comprising: providing a secondary side controllable switch in series between said secondary winding and said power output; sensing, on said secondary side of said forward switch mode power converter, a signal dependent on said output current or voltage of said power converter; and controlling an on-off switching of said secondary side controllable switch responsive to said sensing of said signal dependent on said output current or voltage, to control a proportion of said power cyclically switched by said primary-side switch transferred to said power output to thereby regulate said output voltage or current.

The power converter may be a forward converter (i.e. with matched polarity transformer windings), in which case the secondary side switch may be coupled in series with the output, as previously described.

The invention also provides a power converter incorporating means to implement the above-described method.

Thus in a further aspect the invention provides a power converter with output regulation, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer; the power converter further comprising a secondary side controllable switch on said secondary side of said power converter coupled to, when switched, reduce a power delivered to said power output; a sensing system, on said secondary side of said forward switch mode power converter, a signal dependent on said output current or voltage of said power converter; and a controller to control an on-off switching of said secondary side controllable switch responsive to said sensing of said signal dependent on said output current or voltage, to control a proportion of said power cyclically switched by said primary-side switch transferred to said power output to thereby regulate an output voltage or current of said power converter.

In embodiments of the above-mentioned methods and apparatus the techniques described may be implemented using either analogue or digital circuitry or a combination of both these. Often an analogue implementation will be preferred for cost reasons, but the skilled person will appreciate that, broadly speaking, corresponding techniques may also be implemented by digital circuitry, generally speaking in a broadly similar manner, and that in implementations this may also be cost effective, for example where much or all of the relevant primary and/or secondary side circuitry is implemented on a single integrated circuit.

The invention therefore also provides a controller for a forward switch mode power converter configured to implement a method according to any one or more of the aspects and embodiments of the invention as described above. In embodiments such a controller is implemented as an integrated circuit (IC).

For each of the aspects and embodiments of the invention described above a particularly preferred implementation comprises a resonant discontinuous forward converter (RDFC). We have described some preferred techniques for implementing an RDFC in co-pending US patent applications 11/449,486; 11/639,827; 11/732,140; 11/732,108; 11/732,107; and in GB 0708196.1; GB 0708202.7; GB 0708198.7; GB 0708112.8; and GB 0708200.1; all hereby incorporated by reference in their entirety.

The skilled person will further appreciate that features of aspects and embodiments of the invention as described above may be combined.

## BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects of the invention will now be further described, by way of example only, with reference to the accompanying figures in which:

Figure 1 shows an example of a forward power converter according to the prior art;

Figures 2a to 2d show, respectively, an example of a resonant discontinuous forward converter (RDFC) incorporating a primary-side switch controller, details of an example controller, waveforms illustrating the operation of the RDFC of Figure 2a, and an example implementation of an RDFC using a single-chip controller integrated circuit (IC);

Figure 3 shows an example of a base drive circuit for a forward power converter using a bipolar transistor as a primary-side switching device;

Figure 4 shows an equivalent circuit of a forward power converter of the general type shown in Figure 2d;

Figures 5a and 5b show, respectively, a forward power converter configured to regulate the output voltage by sensing on an auxiliary winding when the primary-side switch is on, and a detailed circuit illustrating implementation of the controller of Figure 5a;

Figure 6 shows an example of a forward power converter configured to sense an auxiliary winding voltage using a controller power supply current;

Figures 7a to 7c show, respectively, a resonant primary or auxiliary winding voltage during a primary-side switch off period illustrating voltage clamping by secondary-side output diode conduction, a first example of a forward power converter configured to sense a secondary-side voltage when the primary-side switch is off, and a second example of a forward power converter circuit configured to sense a secondary-side output voltage when the primary-side switch is off using a shared sensing/power supply pin on a controller IC;

Figures 8a to 8c show, respectively, an example of a secondary-side circuit including a capacitor to facilitate output voltage regulation of a forward converter and example waveforms illustrating the operation of circuit of Figure 8a for short and long on periods of the primary-side switch respectively;

Figures 9a to 9c show, respectively, a simplified circuit of a forward power converter, the circuit including secondary-side series output inductance and waveforms illustrating varying power delivered to the load;

Figures 10a to 10c show, respectively, a forward converter including a flywheel diode, a simplified illustration of a forward converter including a secondary-side switch, and a flywheel diode;

Figures 11a and 11b show, respectively, a first example of a forward converter including a secondary side switch and secondary-side sensing and control circuitry for controlling the secondary-side switch, and a detailed block diagram illustrating the operation of an embodiment of the arrangement of Figure 11a; and

Figure 12 shows a second example of a forward power converter including a thyristor as a secondary-side switch.

# DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

We will describe techniques which are particularly applicable to forward converters, especially off-line converters where isolation between the primary (source) side and secondary (load) side is strongly desirable. However some of the techniques we describe, in particular those using a secondary-side switch, are not limited to forward converters and may also be applied, for example, to fly-back converters.

## Resonant discontinuous forward converters

Referring to Figure 2a, (which is taken from our earlier application US 11/639,827), this shows an example of resonant discontinuous forward converter (RDFC) 200; Figure 2b shows an example timing and control system 210 for the converter. A dc input 202 coupled to the primary winding 204 of a transformer 206, connected in series with a power switch 212. A resonant capacitor 214 is connected across the primary winding of the transformer and the dc input 202 is provided with a smoothing capacitor 216. On the output side of the forward converter a secondary winding 208 of the transformer provides power to a pair of dc output terminals 218 via a rectifier 220. A smoothing capacitor 222 is connected across the dc output terminals 218 and an output node at the junction of rectifier 220, smoothing capacitor 222 and a connection to one of the dc output terminals 218 is denoted "X". The current into node X, which flows to either or both of the smoothing capacitor 222 and output 218, is discontinuous.

The switch 212 may comprise a bipolar or MOS transistor for example a MOSFET, IGBT, or BJT.. The rectifier 220 may be implemented as a diode ,MOS transistor or other semiconductor switch. The resonant capacitor 214 may either comprise a discrete component, or may be entirely provided by parasitic capacitance, or may be a combination of the two.

The switch 212 is controlled by a controller 210 comprising a timing control module 210a and a switch control module 210b, the timing control module providing switch on and switch off signals 210c to the switch control module 210b. The timing control module may have one or more sense inputs, such as a voltage sense input and a current sense input as illustrated, or such sensing may be omitted and the timing control module 210a may operate substantially independently of any sensed condition of the forward converter circuit. Using a controller 210 to control the timing of the switch 212 on and off allows a variety of advantageous control techniques to be employed including, for example, current limiting, start-up control and regulation. The controller may, for example implement one or more of pulse amplitude, pulse width, pulse frequency, and variable slope modulation to control the switching device.

In operation the circuit of Figure 2a converts the input dc voltage, typically relatively high, to an output dc voltage, typically in a range suitable for consumer electronic devices, for example between around 5V and 20V. Preferably the dc output is isolated from the dc input, as shown.

Figure 2b illustrates an example implementation of the controller 210 of Figure 2a. A comparator 250 compares a sensed voltage representing resonance associated with the transformer with a reference voltage, for example zero volts, to provide a control signal 252 to a switch control unit 256 to control switch 212 on. The output of comparator 250 is also provided to a timer 258 which begins timing an on pulse width. When the timer times out a signal is provided on a second control line 254 to switch control unit 256 to control switch 212 off. Switch control unit 256 may comprise, for example, a set-reset latch together with interface circuitry for driving the base of a bipolar transistor and/or the gate of an MOS transistor. The controller may include an OR gate 260 with an input 262 from an over current protection line. This input may be generated by a comparing a current sense input with a reference level defining a threshold for current limiting. Thus in this example when the over current protection input 262 becomes active the switch control unit 256 is immediately controlled to switch 212 off, thus implementing cycle-by-cycle current limit control.

Figure 2c shows the switch being turned on at close to 0V (point “B” in the Figure). This provides optimum power transfer. One or both of the on-time and off-time of the switch may be adjusted to control the power transfer, but preferably the off-time is chosen to correspond to the resonance period of the switch voltage.

Figure 2d shows more details of an example RDFC, including a single-chip controller integrated circuit (IC) and a resonant capacitor 272, also performing a sensing function as described further below. An auxiliary winding, rectifier and capacitor 274 are used to derive an auxiliary supply Vaux for powering the controller chip 270. A current sensing resistor 276 connects to a current sense (CS) pin on IC 270.

**Base drive control**

Use of a bipolar switching resistor in a power converter can provide a significant cost saving as compared with, say, a power MOSFET, but with a bipolar transistor it is desirable to manage carefully the on-state conditions. It is useful to vary the on-state base current in response to the on-state current and/or transistor gain so that the delivered base current is sufficient to support the on-state conditions at low on-state voltage but is not excessive, to facilitate a fast turn-off.

Figure 3 shows a circuit for a power converter taken from our earlier UK patent application GB0708196.1 filed 27 April 2007 (hereby incorporated by reference), including, at the bottom, details of an example sensing and base drive circuit. Referring to Figure 3, the power converter 300 having (in this instance) an AC input from a grid mains supply 302 which is rectified and smoothed to provide DC power on line 304 to the primary winding of a transformer 306, switched by bipolar transistor 308, Q1. The secondary winding of transformer 306 is rectified and smoothed to provide a DC voltage output 310.

A sensing element 312 ( such as a capacitor) senses the collector voltage of transistor 308 (Q1) and provides a sensed voltage signal output (Col) on line 313 to a controller 314 which has, as a second input, a reference level, as illustrated a reference voltage $V_{REF}$. The signal on the Col line has a value which is dependent on the sensed collector voltage and, in embodiments in which the system is implemented on an integrated circuit, may be brought out on a pin of the IC. The controller has an output 316 to a modulator 318 which provides a base drive signal 320 to the base (or gate) of transistor 308 modulated by switch 322, which may for example be implemented using a

MOSFET. Switch 322 is controlled by a DRIVE signal from controller 324 which, in the illustrated example, has a sense input 326 also from the collector of transistor 308.

The base current is controlled by monitoring the voltage at the collector of the BJT (bipolar junction transistor) during the on-time of the primary switch (BJT). The aim is to control the amount of base current so that the voltage at the collector pin is set equal to the threshold voltage ($V_{REF}$) just before turn-off. Further details are described in our earlier application (*ibid*).

**Primary side voltage regulation**

One source of source of output voltage variation is the incoming supply. The effect of varying input voltage could be corrected by sensing the voltage, comparing it to a stable reference, and then varying the duty cycle according to some preset law. This is in principle simple but is not accurate as the law would need to be carefully matched to the system characteristics. A better approach would be to sense the output voltage, compare it to a reference and adjust duty cycle accordingly. However transferring an error signal across an isolation barrier between the primary and secondary sides of the power converter is expensive and we will describe techniques using signals on the primary or on an auxiliary winding to detect errors in output voltage.

During the primary side switch on-period, the transformer equivalent circuit of a forward converter, for example of the type shown in Figure 2d, can be regarded as shown in Figure 4 (with all signals referred to the primary), in which:

Zpri, Zaux and Zsec represent the equivalent series impedances of the windings (particularly leakage inductance);
Zmag is the magnetising impedance;
Daux and Caux are the auxiliary supply rectification and smoothing; Raux is the auxiliary load; and
Dout is the main output rectifier.

If Raux is a relatively low load, then the voltage across Zaux is small. Hence the voltage from the auxiliary winding then depends on the relative sizes of Zpri, Zsec and the source and load voltages. If Zsec is small in comparison to Zpri the auxiliary voltage substantially varies with the output voltage and may not be substantially affected by the source voltage. The controller can thus monitor the auxiliary voltage during the on period to determine the approximate output voltage hence can adjust the duty cycle to regulate it (during the on state an auxiliary winding voltage is measured because the primary winding voltage is, essentially, the source voltage). Advantageously, by design of the transformer, in particular by bifilar winding of the Auxiliary and Secondary windings, Zsec can be minimised in comparison to Zpri.

Errors in output voltage then are caused by voltage drop in the output diode and by voltage drop in Zsec. During the on period both of these are dependent on the primary current so, in embodiments, may be corrected by an allowance for primary current sensed by the controller. It can be particularly useful if the correction factor is programmable. Thus, broadly, the primary supply is used to predict losses in the secondary side of the converter, and hence compensate for this in the measured Vaux.

Referring to Figure 5a, this shows an embodiment of a forward converter 500 configured to implement such a control technique. The supply Vsource may be derived from an ac mains supply as previously described. A controller 502 (along similar lines to those described above) monitors signal Vsense, comparing it to a fixed reference and adjusts the converter duty cycle in response to differences: a higher Vsense causes a reduction in duty cycle to reduce the output voltage.

Primary winding 504a of transformer 504 is switched by a bipolar switching device 506, for example as previously described, and the output Vout is derived from a secondary winding 504b via a rectifier 220 and smoothing capacitor 222, again as previously described. An auxiliary winding 504c provides power Vdd to controller 502 via a rectifier Daux and smoothing capacitor Caux and resistor Rdd (Raux in Figure 4).

Primary current through current sense resistor Rs produces a signal Isense, used by the controller to limit power duty cycle and power delivery in overload conditions, for example as described above. Resistor network Rc1, Rv1 and Rv2 combine the auxiliary supply voltage and Isense to produce signal Vsense. Resistors Rv1 and Rv2 form a potential divider and in the absence of Rc1, Vsense is simply a proportion of the auxiliary supply voltage, and regulation would be possible but output voltage errors would be caused by variable load current. By including Rc1, the effect of load current can be compensated. In the on state, if the output draws more current there is more voltage drop and Vout falls and thus the voltage on the auxiliary winding (Vaux) also falls, although not enough because the coupling to the secondary winding is not perfect. If more current is drawn the controller should adjust the converter to deliver more power; coupling a negative voltage (referenced to GND) to the Vsense input, via Rc1, achieves this. The value of Rc1 (in comparison to Rv1/Rv2) can be adjusted to vary the degree of compensation. Compensation, though effective, is not perfect due to component tolerances, non-linearities (e.g. in the output diode), effects of temperature and other second order effects.

An example of circuitry to implement the control method for controller 502 is shown in more detail in Figure 5b.

Amplifier A2 compares a fraction of the voltage from the auxiliary winding to reference voltage (Vref2). Primary current flows through sense resistor Rs so the negative voltage (current signal) at node “C” is a measure of the current. Rc1 couples this to the input of A2, node “D”. Amplifier A1 compares the current signal to reference Vref1. The polarity of the amplifiers and the coupling via D1 and D2 are arranged so that the voltage of input B of the timing generator increases if:

Either the signal current rises above Vref1
Or the voltage at node “D” rises above Vref2.

In the example of Figure 5b, Vref1 is a negative voltage with respect to GND and the Vs polarity is negative to node C and positive to the transformer. The resonance detector and timing generator operate with the remaining circuits to form a resonant discontinuous forward converter, for example as described in patent applications (*ibid*). Input B of the timing generator, which may carry several signals, synchronises turn-on/off of Q1 for proper converter operation. Input A is a control input that varies the on/off ratio of the converter; a higher voltage at A reduces the on time and/or increases the off time of the switching transistor Q1.

In operation, if the output voltage is higher than desired, then the voltage from the auxiliary winding will be high, hence likewise node D. This causes a reduction of on-time or increase of off-time of Q1, so reduces power delivered to the secondary circuits, reducing the output voltage. Likewise, if the primary current is high, the output of A1 is high, again causing a reduction of power delivered to the secondary, so limiting the output current. Before this current limit comes into effect, an increase in load current will cause a fall of the voltage at node C during the on-period. This couples to node C so that a higher auxiliary voltage is required to balance the voltage at node D with Vref2. Hence the coupling via Rc1 causes an increase in on/off duty of Q1 when the load is increased. This effect can be used to compensate for the reduction of output voltage relative to the auxiliary voltage that typically occurs with increasing load current.

Where regulation accuracy is less critical, a simplification of the circuit is possible. Typically, the controller includes a shunt regulator to stabilise its supply voltage (Vdd). In this case, the current through supply resistor Rdd can be used to sense the rectified auxiliary voltage. Figure 6 (in which like elements to those of Figure 5 are indicated by like reference signs) shows an embodiment of a forward converter 600 to implement such a technique.

Preferably, circuits within the controller monitor the connection current, Idd, because this is most directly related to output voltage. If the shunt regulator current (Ireg) is high in comparison to current used by other internal circuits then the regulator current Ireg can be used instead of Idd because there is only a small error in assuming Ireg = Idd. In either case the sensed current is used to sense the output voltage; low output voltage being represented by low current. As a result of comparing the current to an internal reference, the duty cycle of the converter can be adjusted automatically to regulate the output voltage.

Load current will always affect monitoring of the secondary voltage by primary signals during the on period. An alternative is to sense the output voltage when circuit currents are low. Referring to Figure 7a an example is to sense the primary or auxiliary winding voltages at the end of the off period resonance, but before the primary switch is turned on again. In conditions of strong resonance (longer on time), the resonance amplitude is sufficient to bring the output diode back into conduction, as shown by the secondary voltage clamp level in Figure 7a, when the output voltage can again be "seen" by the auxiliary winding.

During the period when the primary switch is off, the transformer primary voltage resonates about the DC supply voltage until the secondary voltage rises to cause conduction in the output diode. At this point, the voltage across the primary can be used to sense the output voltage. The currents in primary and secondary come from the magnetising current so are typically much lower than load currents. Hence voltage errors due to leakage inductance are low. Voltage drop in the output diode will cause an error but in many applications this can be compensated adequately by assuming it to be a fixed voltage. In operation, the controller samples the sense voltage at the end of resonance when the output diode has clamped the primary voltage but before the controller turns on the primary switch. The sampled voltage is compared to a reference and the duty cycle increased or decreased as required to regulate the voltage. The resonance should be sufficiently strong to cause output diode conduction. This may not be the case when the on period has been shortened too far. To address this one can, for example, restrict the minimum on period or disable this regulation method for short on periods.

Sensing the primary voltage can be difficult when the supply voltage is high. An alternative is to use a further (auxiliary) winding 504d to sense output voltage. Conveniently this can be connected to the ground reference of the controller to produce a positive voltage when the output diode clamps the resonance voltage. Further, this winding can be wound close to the secondary to minimise leakage inductance, improving accuracy of voltage sensing. Particularly if this winding has the same number of turns as the secondary and is provided with a further similar or matched rectifier Daux2 then the resulting DC voltage will be a more accurate representation of the output voltage. The sensing function can also be combined with provision of auxiliary power to the controller, using either a common rectifier or, for greater sensing accuracy, separate rectifiers, as shown in Figure 7b (again like elements are shown by like reference signs).

In the forward converter 700 of Figure 7b the auxiliary supply and sense voltages are taken from different tappings on the third winding. This allows the auxiliary voltage to be set for optimum efficiency while the sense winding remains matched to the secondary for accurate sensing of voltage.

Where the controller is implemented as an integrated circuit it is preferable to minimise the number of pins to minimise cost. In some embodiments it is possible to use a single pin (Aux/Vsense)for both voltage sensing and auxiliary supply. Figure 7c shows a forward power converter 750 configured to implement this technique. When the switch (Q1) is on the AUX/Vsense pin may be used to provide drive current to the switch (from pin BAS) to drive the switch on. This pin thus provides a second power supply (in addition to Vdd) for the controller for driving the switch. When the switch (Q1) is off, a low current is drawn via this pin so its voltage may be used to sense a voltage on an auxiliary winding of the transformer 504.

Referring to Figure 7c, transistor Q2 provides current to the AUX/Vsense pin during the on period. Internally, the controller passes this current though to the BAS pin to turn on the primary switch Q1. During the off period, there is no draw of AUX current so the pin can be used to sense voltage. Rv1 and Rv2 divide the voltage from the auxiliary winding to match the operating range of the AUX/Vsense pin. During sensing, the voltages are arranged so that Q2 passes no significant current. This can be done by setting the comparison reference voltage significantly higher than the working AUX voltage during the on period; for example it could be set to be the same as the Vdd voltage. Thus transistor Q2 operates as a series regulator, to provide current when needed by the Aux/Vsense pin but when the switch (Q1) is off, Q2 is also off and thus in the off period Daux2 in conjunction with Rv1 and Rv2 measure the secondary side voltage.

## Output inductance

Adding an output inductance can facilitate a margin of voltage regulation: Output voltage regulation of an RDFC is facilitated when there is a significant effective inductance between the power source and the load but a problem arises when the primary switch turns off when significant current is flowing. Then series inductance (for example transformer leakage inductance) causes a fast rise of switch voltage, possibly to destructive levels. A technique for addressing this problem is shown in Figure 8a.

In the arrangement of Figure 8a current through Ls is continuous and the value of Cz is chosen so its voltage falls significantly during the off period, as shown in the timing diagrams of Figures 8b and 8c, which illustrate short and long switch on-times respectively. As can be seen, in the latter case the mean Cz voltage is higher than in the former.

Still referring to Figures 8b and 8c, during the on period, the Cz voltage charges rapidly to the supply input voltage, scaled by the transformer ratio and after small losses due to switch and diode drops. During the off period it falls at a rate determined by the load current. If the on period is increased, but the off period is kept approximately constant as a result of the resonance, the wave shape changes so that its mean value increases. Ls and Cout smooth the Cz voltage for delivery to the load. This allows some change of output voltage but the inclusion of Cz substantially avoids inductive energy being fed back through the transformer at turn off.

## Secondary-side switches for power regulation

A switching device in series between the secondary of the transformer and the load provides a means to regulate power delivered to the load. Regulation may be performed on the basis of voltage at the load or current delivered to the load, all measured on the secondary side without need for additional galvanic isolation of control or error signals.

The basic arrangement of an isolated forward converter is shown in Figure 9a. Power from the source 1000 (which may be rectified ac mains) supplied to the primary 1002a via the primary switch 1004, which chops it into AC for transmission through the transformer 1002. The voltage from secondary 1002b is rectified by rectifier 1006 and smoothed by capacitor 1008 for delivery to the load 1010. By choice of the turns ratio of transformer the nominal output voltage can be adjusted in relation to the supply voltage.

This arrangement has no active voltage regulation. If the supply voltage changes in the secondary then the load voltages change accordingly. In addition, as the load current increases the voltage delivered to the load reduces as a result of circuit resistances and leakage inductance of the power transformer.

The arrangement for Figure 9b includes secondary side output inductance, Ls. The series inductance and resistance causes unwanted voltage drop in unregulated converters but this can be used as a basis for regulation if monitoring of the output conditions is available. The on off duty cycle of the primary switch can be varied to change the power delivered to the load (see Figure 9c). During the on-phase of the switch, current builds in the secondary circuit according to the series inductance and resistance and the mismatch between input and load voltage. More power can be delivered to the load by increasing the on-period of switch. In the configurations shown, this series inductance Ls may be implemented either as a separate component or simply via the leakage inductance of the transformer.

Another configuration, shown in Figure 10a, adds a flywheel diode 1012 and discreet output inductor 1014 to the output circuit. In this case the inductor provides ample current during part or all of the off-period of the primary switch. The advantage of the system is increased power delivery and reduced output circuit ripple current.

In a forward converter, with or without flywheel diode, power delivery can be controlled not only by a primary switching the primary circuit but also by a switch 1104 inserted in the secondary circuit, as illustrated substantially in Figures 10b and 10c.

Power can be transferred to the load substantially only when both the primary switch and the secondary switch are closed. In the context of using a flywheel diode, a secondary side switch can be connected in series with the main secondary rectifier, as shown in Figure 10b.

These, therefore, provide a basis for "secondary-side regulation" where sensing of load conditions and controlling power flow can be accomplished using a circuit only connected to the secondary side.

One arrangement of a forward converter 1100 configured to implement secondary side regulation is shown in Figure 11a. In Figure 11a a control block 1102 on the secondary side monitors the voltage across the load and the current supplied to the load (via series current sense resistor Ris). It varies the timing of the secondary switch 1104 to regulate the voltage across the load and reduce power delivered to the load when the sensed load current rises too high. Either or both of voltage and current control may be implemented. An example of the circuitry in control block 1102 is shown in more detail in Figure 11b.

Referring to Figure 11b differential amplifiers U4 and U5 compare, respectively, the load current and voltage against references Vref2 and Vref3. Scaling by Rs and Rv1/Rv2 presets the limit output current and voltage. If either load current or load voltage rise above these preset values, the voltage at node "A" rises. A digital timing reference signal is derived from the transformer secondary signal via comparator U1. This triggers a ramp generator, whose output voltage rises during the on-period of the primary switch. Comparator U3 operates the secondary switch in response to the voltage at node A. If the voltage rises, the turn-on time of the secondary switch is delayed, reducing power delivered from the transformer, so stabilising output current and/or voltage.

Power can be transferred to the load substantially only when both switches are turned on, and therefore the control of the secondary switch is synchronised to that of the primary switch. This can be done using the voltage from the secondary of the transformer. Referring to the polarities of Figure 11a, the voltage at the secondary of the transformer (relative to "ref") is positive when the primary switch is turned on. In general, the rising edge of the secondary voltage can be used to indicate the turn-on time of the primary switch and operation of the secondary switch can be synchronised to this. When the primary switch turns off the voltage at the secondary of the transformer reverses due to the effect of the magnetising current in the transformer inductance. Again, this can be sensed so the secondary-side control circuit can synchronise to primary switch turn-off. To reduce power delivered to the load, the operating period of the secondary switch can be varied either by delaying the turn-on or advancing the turn-off of the secondary switch. In the case of advancing the turn-off of the switch the control circuit can estimate the turnoff instant of the primary switch in the present on-phase. Preferably this is done by measuring the primary switch on-period in previous converter cycles and using this as a basis for the estimate in the present cycle. Preferably, control of the primary switch is done at substantially constant, or slowly changing frequency.

This system can be used with or without a flywheel diode and with the output circuit operating in either continuous or discontinuous-current mode. It is also compatible with power-saving techniques such as reduction of the primary switch duty cycle at lower loads (techniques for RDFC power regulation are described in our patent application no. 11/732,108 incorporated by reference). When low-power is drawn by the load, a correspondingly low-power is drawn from the primary circuit and this can be sensed to cause a reduction of the primary switch duty cycle. However, if the power sensing on the primary side is performed by sampling primary current at an instant during the converter cycle; then the secondary circuit timing should be arranged to draw load-related current at that instant.

Choice of an appropriate device for the secondary switch preferably takes account of power capability, cost, control means and control power required. Choices include: MOSFET, bipolar junction transistor, thyristor/triac and the like. In applications intended to avoid the cost of an isolating component, cost may be an important factor. An example of a low-cost voltage-regulating circuit 1200 using a thyristor is shown in Figure 12.

Referring to Figure 12 diode D1 and C1 provide a low-power bias for gate turn-on of thyristor TH1, 1202, i.e. diode D1 and capacitor C1 provide a bias voltage (greater than the voltage on the load) so that there is always potentially gate current available for TH1 via resistor R1. Power is delivered to the load from transformer T1 through diode D2 inductance L1 and the thyristor. The voltage at the load is monitored by a voltage reference device 1204 which may be, for example, a shunt regulator such as the Fairchild (RTM) TL431 which, similar to a zener diode, draws current in line 1204a when the voltage on line 1204b exceeds a (programmable) reference. If the load voltage is higher than the target voltage set by the voltage reference, the voltage reference draws current from the R1/TH1 gate node. This prevents triggering of the thyristor so reducing power to the load, - if there were no regulation TH1 would automatically switch on at the start of each cycle (and off at the end) because when the secondary winding voltage exceeded the load voltage current would flow into the gate via R1 (and out towards the load). Operation of the circuit is simple, if the load voltage is too high the thyristor does not conduct (the shunt regulator robs TH1 of gate current), thus losing a cycle; if it is too low the thyristor triggers in each converter cycle passing power to the load. Inductance L1 is preferably chosen to provide an adequate range of voltage difference between the transformer secondary voltage and the target load voltage for regulation, taking into account the load current and the on-time of the primary switch (preferably at maximum load and on time the secondary winding voltage is larger than the load voltage) whilst TH1 is on). If the operating frequency is relatively low (for example around 30kHz or less) then it may be possible to combine the functions of TH1 and D2 as a single thyristor. At higher frequencies, the turn-on and turn-off delays of the thyristor may be unacceptable in which case an additional (faster) rectifier may be used.

These techniques are particularly suitable for (but not limited to) forward converters which have galvanic isolation between the input and output, for providing output voltage and/or current regulation. Embodiments include a series switching element in the secondary between the transformer and the load but do not pass any error/control signal across the isolation barrier, and do not require an additional transformer or signal isolating device. Thus in embodiments output regulation may be provided without substantial extra cost.

No doubt many other effective alternatives will occur to the skilled person. It will be understood that the invention is not limited to the described embodiments and encompasses modifications apparent to those skilled in the art lying within the spirit and scope of the claims appended hereto.

## CLAIMS:

1. A method of regulating the output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output; and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output and a secondary side rectifier; the method comprising:

sensing a voltage on said primary winding or on an auxiliary winding of said transformer during a period when said switch is off and said secondary side rectifier is conducting; and

controlling a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

2. A method as claimed in claim 1 wherein said power converter comprises a resonant discontinuous forward converter, wherein said voltage on said primary winding or auxiliary winding is substantially resonant, and wherein said sensing comprises sensing adjacent an end of a cycle of said substantially resonant voltage.

3. A method as claimed in claim 1 or 2 wherein said sensing comprises sensing a voltage on said auxiliary winding via a second rectifier.

4. A method as claimed in claim 1, 2 or 3 further comprising deriving an auxiliary supply for driving said switch on from a circuit node of said power converter, drawing substantially no current from said circuit node for driving said switch when said switch is off, and using said circuit node for said voltage sensing when said switch is off.

5. A controller for controlling an output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said

transformer to transfer power to said power output via said secondary winding of said transformer and a secondary side rectifier; the controller comprising:

a circuit to sense a voltage on said primary winding or on an auxiliary winding of said transformer during a period when said switch is off and said secondary side rectifier is conducting; and

a circuit to control a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

6. A forward switch mode power converter including a controller as claimed in claim 5.

7. A method of regulating the output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer, and wherein said transformer includes an auxiliary winding; the method comprising:

sensing a voltage on said auxiliary winding of said transformer during a period when said switch is on to sense said output voltage; and

controlling a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

8. A method as claimed in claim 7 further comprising compensating, during said sensing, for a change in a value of said sensed voltage on said auxiliary winding relative to said output voltage of said forward converter due to loading of said power output.

9. A method as claimed in claim 8 wherein said compensating comprises adjusting a value derived from said sensed voltage responsive to a current through said switch when said switch is on.

10. A method as claimed in claim 9 wherein said adjusting comprises coupling a signal dependent on said current into a potential divider coupled to said auxiliary winding.

11. A method as claimed in claim 9 wherein said power converter includes control circuitry for controlling said switching, and wherein said sensing of said voltage on said auxiliary winding comprises determining an estimate of said voltage from a current in a power supply from said auxiliary winding to said control circuitry.

12. A method as claimed in any one of claims 7 to 11 wherein said controlling of said proportion of time for which said switch is on comprises controlling a duty cycle of said switching, and wherein said sensing and said controlling are both performed on a primary side of said power converter

13. A method as claimed in any one of claims 7 to 12 wherein said sensing is performed without rectifying said sensed voltage.

14. A method as claimed in any one of claims 7 to 13 wherein said forward switch mode power converter comprises a resonant discontinuous forward converter.

15. A forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer, and wherein said transformer includes an auxiliary winding, and wherein said power converter further comprises a voltage sense circuit to sense a voltage on said auxiliary winding of said transformer during a period when said switch is on to sense said output voltage; and a control circuit to control a proportion of time for which said switch is on, responsive to said sensing, to control said output voltage.

16. A forward switch mode power converter as claimed in claim 9 further comprising a circuit to compensate for a change in a value of said sensed voltage on said auxiliary winding relative to said output voltage of said forward converter due to loading of said power output.

17. A forward switch mode power converter as claimed in claim 15 or 16 wherein said forward switch mode power converter comprises a resonant discontinuous forward converter.

18. A forward switch mode power converter as claimed in claim 15, 16 or 17 wherein said voltage sense circuit is configured to perform said voltage sensing on a primary side of said power converter without rectifying said sensed voltage.

19. A controller integrated circuit (IC) for controlling an output voltage of a forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output, and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer and a secondary side rectifier; said controller IC including a sensing circuit to sense a voltage on said primary winding or on an auxiliary winding of said transformer, a control circuit to control proportion of time for which said switch is on, responsive to said sensing, to control said output voltage, and a switch drive circuit to provide a drive to said switch to turn said switch on; wherein said controller IC has a plurality of external connections; and wherein one of said external connections comprises a multi-functional connection to provide a voltage sense input to said sensing circuit and to provide power for powering said switch drive circuit, both to enable sensing of said voltage and to provide power for said drive to said switch.

20. A controller IC as claimed in claim 19 wherein said voltage sensing circuit is configured to sense a said voltage on said auxiliary winding by sensing a power supply current provided via said multi-functional connection.

21. A controller IC as claimed in claim 19 configured to use said multi-functional connection to, at different times, sense said voltage and provide power to drive said switch, to enable sensing of said voltage when said switch is off and to provide power to drive said switch when said switch is on.

22. A method of regulating the output voltage of a resonant forward switch mode power converter, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer via said secondary winding and a rectifier coupled to said secondary winding to transfer power to said power output, the method comprising coupling an inductor in series between said secondary winding of said transformer and said power output, and operating said power converter such that a voltage on said secondary winding is substantially resonant during an off period of said switch; the method further comprising coupling a first, smoothing capacitor in parallel across said power output on an output side of said inductor and coupling a second capacitor in parallel across a combination of said secondary winding and said rectifier on a secondary winding side of said inductor, and regulating an output voltage of said power supply by varying an on period of said switch such that a consequent variation in a voltage on said second capacitor filtered by said inductor and said smoothing capacitor varies an average value of said output voltage of said power converter.

23. A method as claimed in claim 22 wherein said power converter is a discontinuous converter, and wherein a current through said secondary winding has fallen to substantially zero by the end of said off period.

24. A resonant forward switch mode power converter with a controllable output voltage, said power converter having a power input, a power output to provide said output voltage, a transformer with matched polarity primary and secondary windings coupled between said power input and said power output and a switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output, the converter further comprising: a

rectifier and an inductor in series between said secondary winding of said transformer and said power output; a first, smoothing capacitor coupled in parallel across said power output on an output side of said inductor; and a second capacitor coupled in parallel across a combination of said secondary winding and said rectifier on a secondary winding side of said inductor; and a controller to vary an on period of said switch; and wherein said second capacitor has a value which is sufficiently small that, in operation, a peak-to-peak value of an ac component of a voltage across said second capacitor due to said cyclical switching is at least 10% of an average DC voltage across said second capacitor, and wherein an impedance of said inductor at an operating frequency of said power converter is greater than an impedance of said second capacitor at said operating frequency such that, in operation, variation of said on period of said switch by said controller varies an average value of said output voltage of said power converter.

25. A method of regulating the output current or voltage of a forward switch mode power converter, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer with matched polarity windings coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer; to transfer power to said power output via said secondary winding of said transformer, the method comprising:

providing a secondary side controllable switch in series between said secondary winding and said power output;

sensing, on said secondary side of said forward switch mode power converter, a signal dependent on said output current or voltage of said power converter; and

controlling an on-off switching of said secondary side controllable switch responsive to said sensing of said signal dependent on said output current or voltage, to control a proportion of said power cyclically switched by said primary-side switch transferred to said power output to thereby regulate said output voltage or current.

26. A method as claimed in claim 25 wherein said secondary-side switch is substantially only on at times when said primary-side switch is on.

27. A method as claimed in claim 25 or 26 further comprising sensing, on said secondary side of said forward switch mode power converter, a timing of said cyclical switching on and off of said primary-side switch, and wherein said controlling of said secondary side controllable switch comprises controlling a timing of said on-off switching of said secondary side controllable switch relative to a timing of said on and off switching of said primary-side switch.

28. A method as claimed in claim 27 wherein said controlling of said timing of said on-off switching of said secondary side controllable switch relative to a timing of said on and off switching of said primary-side switch comprises one or both of delaying a turn-on and advancing a turn-off of said secondary-side switch relative to said primary-side switch to reduce said power transferred to said power output.

29. A method as claimed in claim 28 wherein said advancing of said turn-off comprises estimating a turn-off time of said primary-side switch for a present cycle of said cyclical switching from a timing of said turn-off time for a previous said cycle.

30. A method as claimed in claim 25or 26 wherein said secondary-side switch comprises a thyristor and wherein said controlling comprises controlling a gate voltage or current of said thyristor.

31. A method as claimed in any one of claims 25 to 30 further comprising providing an inductor coupled in series with said secondary-side switch to reduce a current through said secondary-side switch due to a mismatch between a voltage on said secondary winding and said output voltage.

32. A forward switch mode power converter with output regulation, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer with matched polarity windings coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer; said power converter further comprising:

a secondary side controllable switch coupled in series between said secondary winding and said power output;

a sensing circuit, on said secondary side of said forward switch mode power converter, to sense a signal dependent on an output current or voltage of said power converter; and

a secondary side control circuit coupled to said sensing circuit and to said secondary side controllable switch to control an on-off switching of said secondary side controllable switch responsive to said sensed signal dependent on said output voltage or current to thereby regulate said output voltage or current.

33. A forward switch mode power converter as claimed in claim 32 further comprising a second sensing circuit, on said secondary side of said forward switch mode power converter, to sense a timing of said cyclical switching on and off of said primary-side switch, and wherein said secondary side control circuit is configured to control a timing of said on-off switching of said secondary side controllable switch relative to a timing of said on and off switching of said primary-side switch.

34. A forward switch mode power converter as claimed in claim 32 wherein said secondary-side switch comprises a thyristor and wherein said secondary side control circuit is configured to control a gate voltage or current of said thyristor.

35. A forward switch mode power converter as claimed in claim 32, 33 or 34 wherein said secondary side control circuit is configured to control said secondary side controllable switch such that said secondary-side switch is substantially only on at times when said primary-side switch is on.

36. A method of regulating the output current or voltage of a switch mode power converter, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer; the method comprising:

providing a secondary side controllable switch on said secondary side of said power converter coupled to, when switched, reduce a power delivered to said power output;

sensing, on said secondary side of said forward switch mode power converter, a signal dependent on said output current or voltage of said power converter; and

controlling an on-off switching of said secondary side controllable switch responsive to said sensing of said signal dependent on said output current or voltage, to control a proportion of said power cyclically switched by said primary-side switch transferred to said power output to thereby regulate said output voltage or current.

37. A method as claimed in claim 36 wherein said power converter comprises a forward power converter with said primary and secondary windings of matched polarity, and wherein said secondary side controllable switch is coupled in series between said secondary winding and said power output.

38. A power converter with output regulation, said power converter having a primary side with a power input, a secondary side with a power output to provide said output voltage, a transformer coupled between said primary side power input and said secondary side power output, and a primary-side switch to cyclically switch power from said power input on and off to said primary winding of said transformer to transfer power to said power output via said secondary winding of said transformer; the power converter further comprising a secondary side controllable switch on said secondary side of said power converter coupled to, when switched, reduce a power delivered to said power output;

a sensing system, on said secondary side of said forward switch mode power converter, a signal dependent on said output current or voltage of said power converter; and

a controller to control an on-off switching of said secondary side controllable switch responsive to said sensing of said signal dependent on said output current or voltage, to control a proportion of said power cyclically switched by said primary-side switch transferred to said power output to thereby regulate an output voltage or current of said power converter.

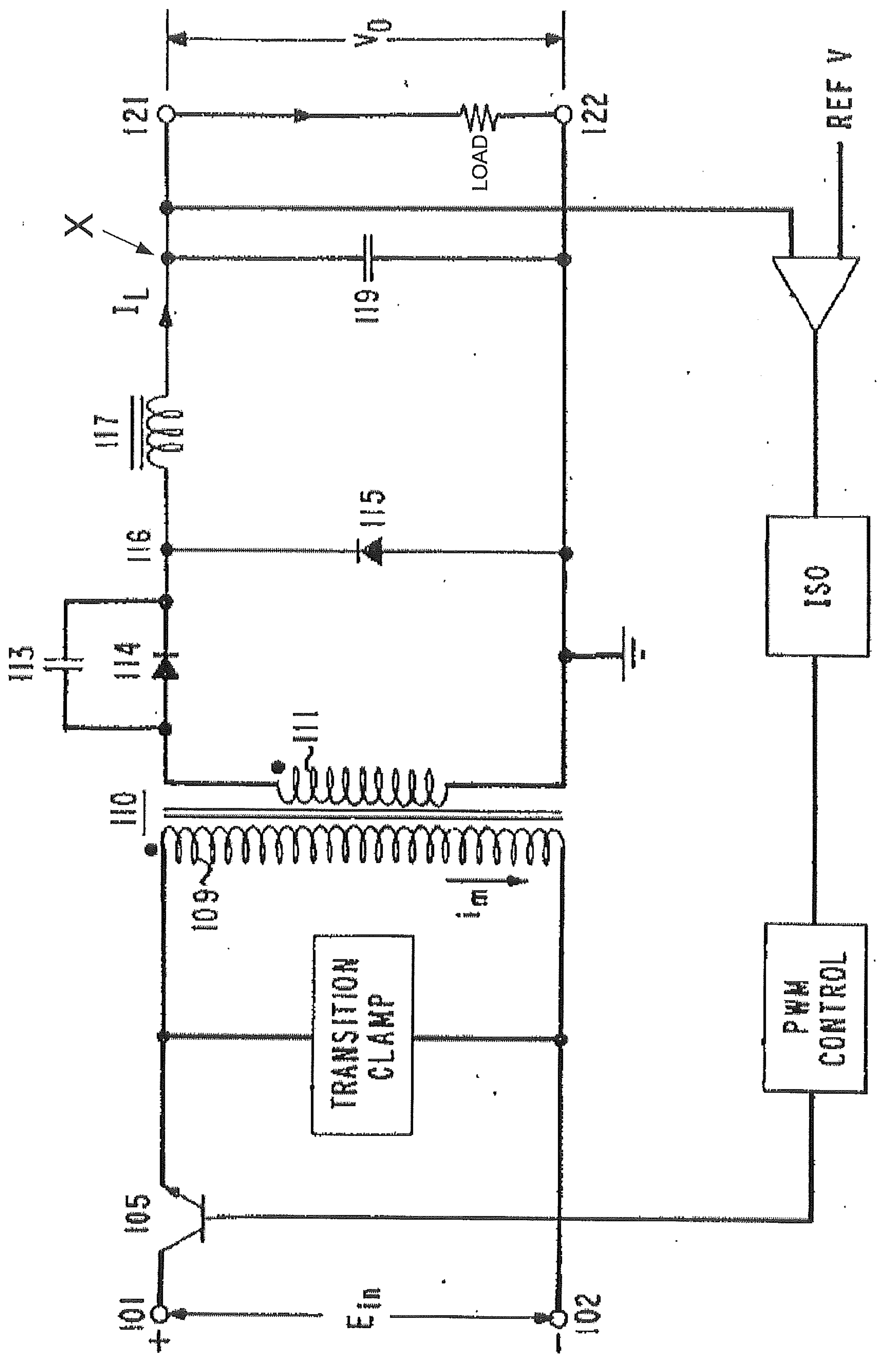


Figure 1
(PRIOR ART)

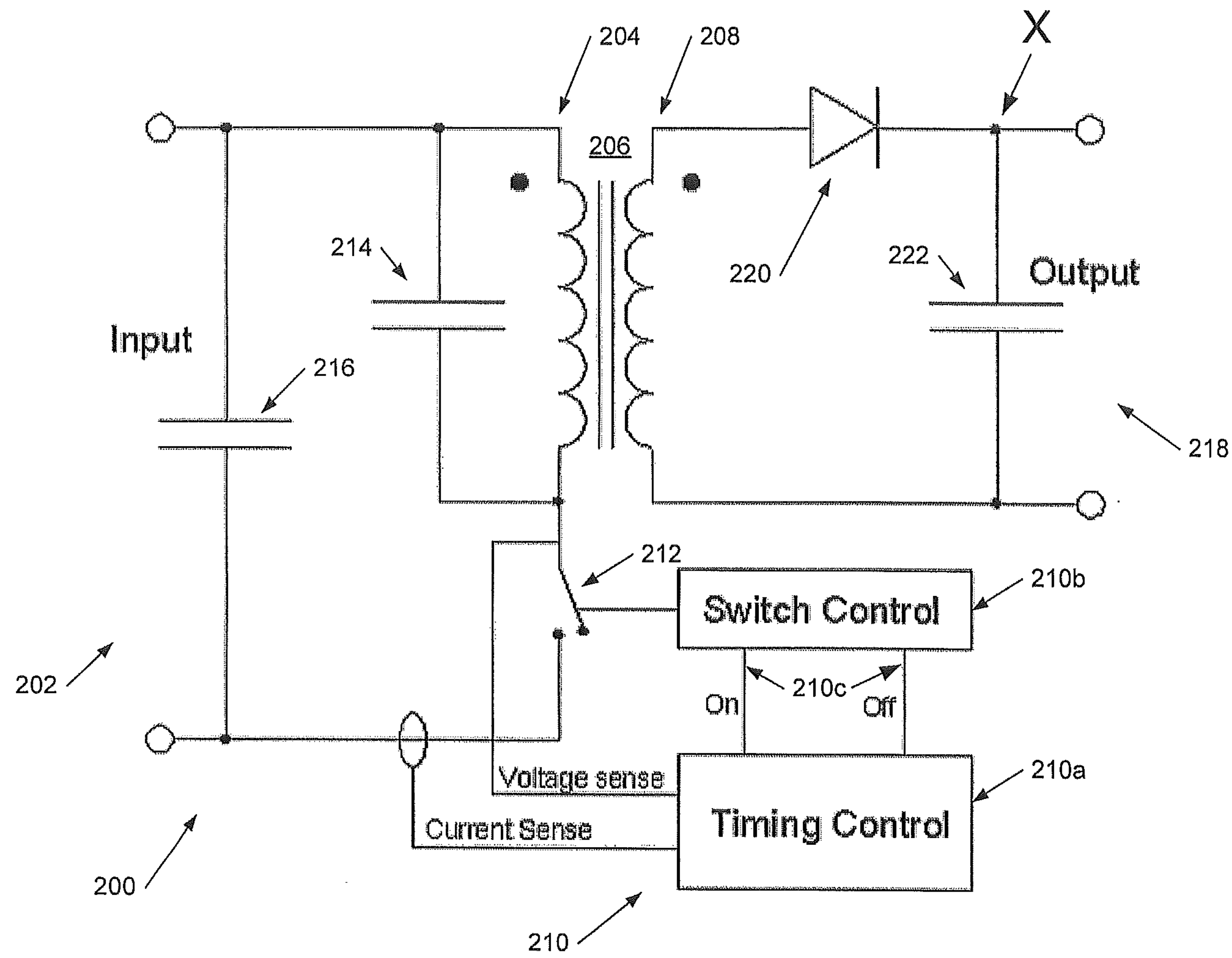


Figure 2a

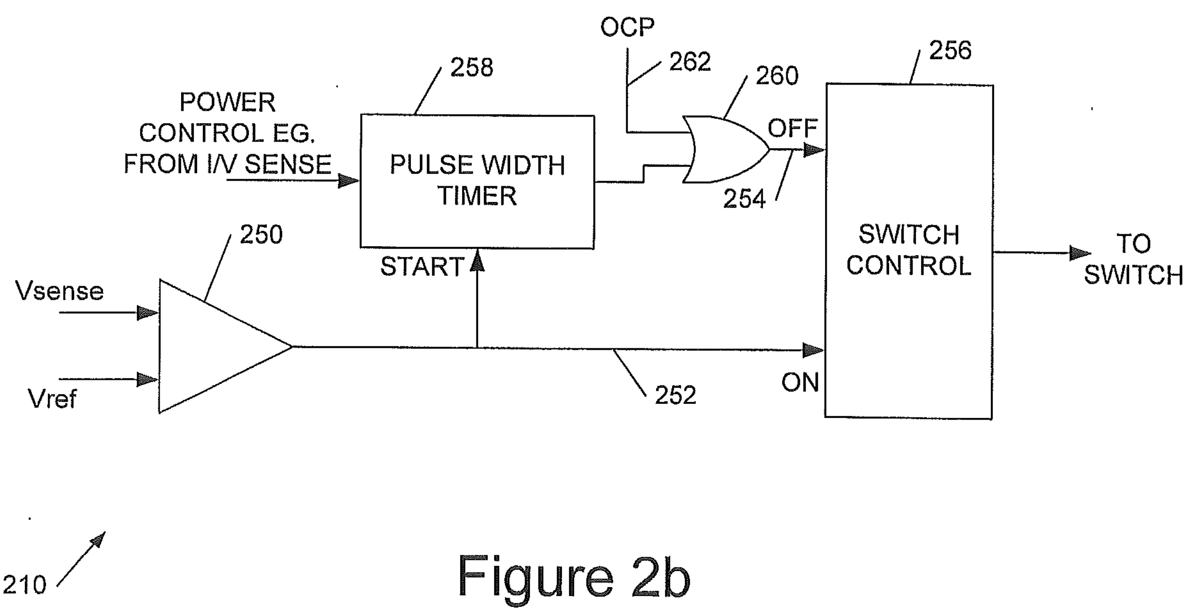


Figure 2b

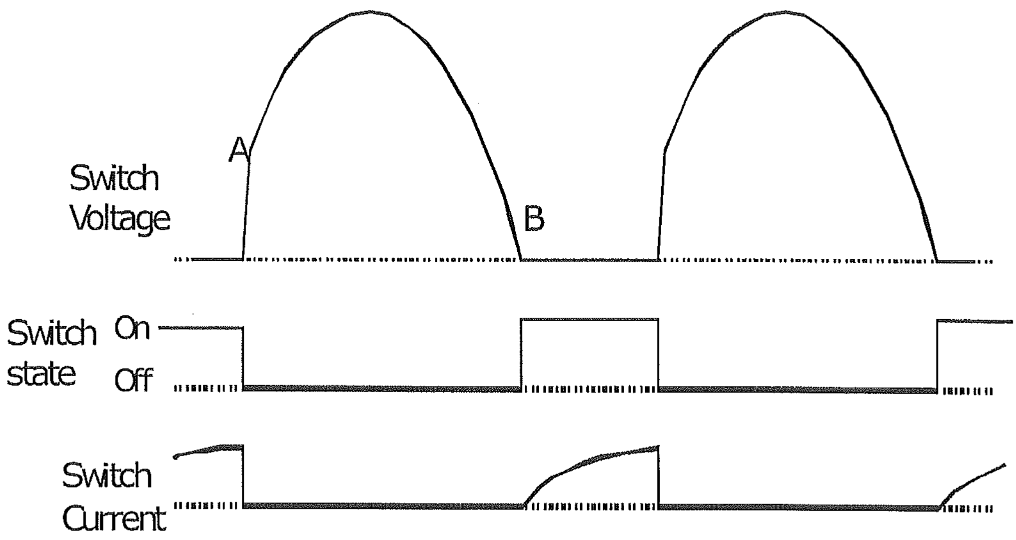


Figure 2c

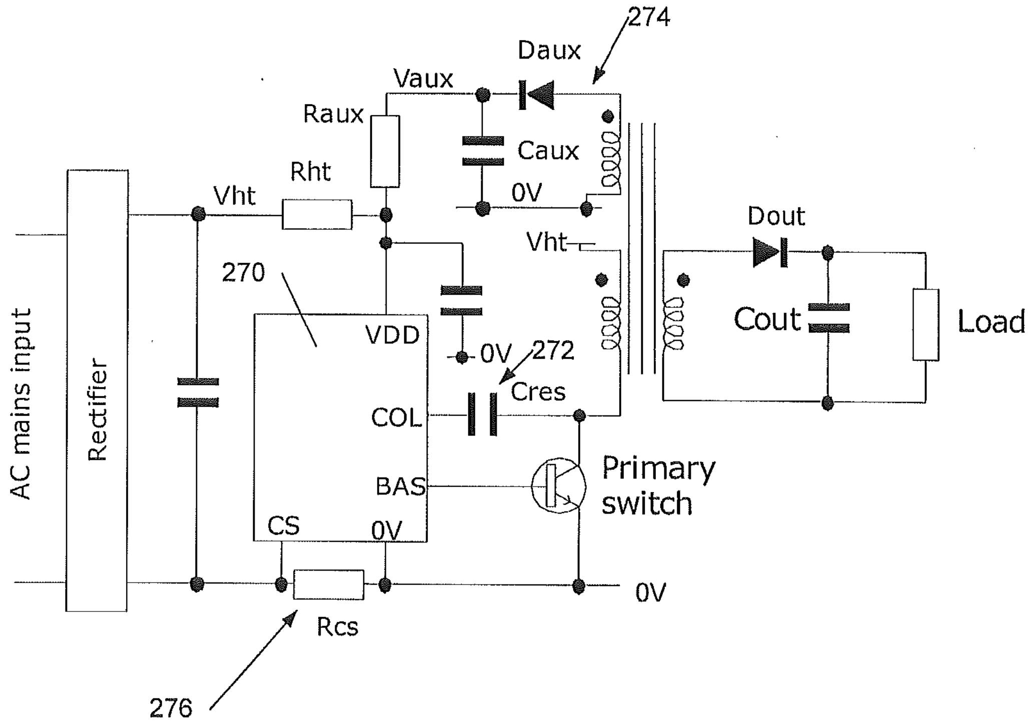


Figure 2d

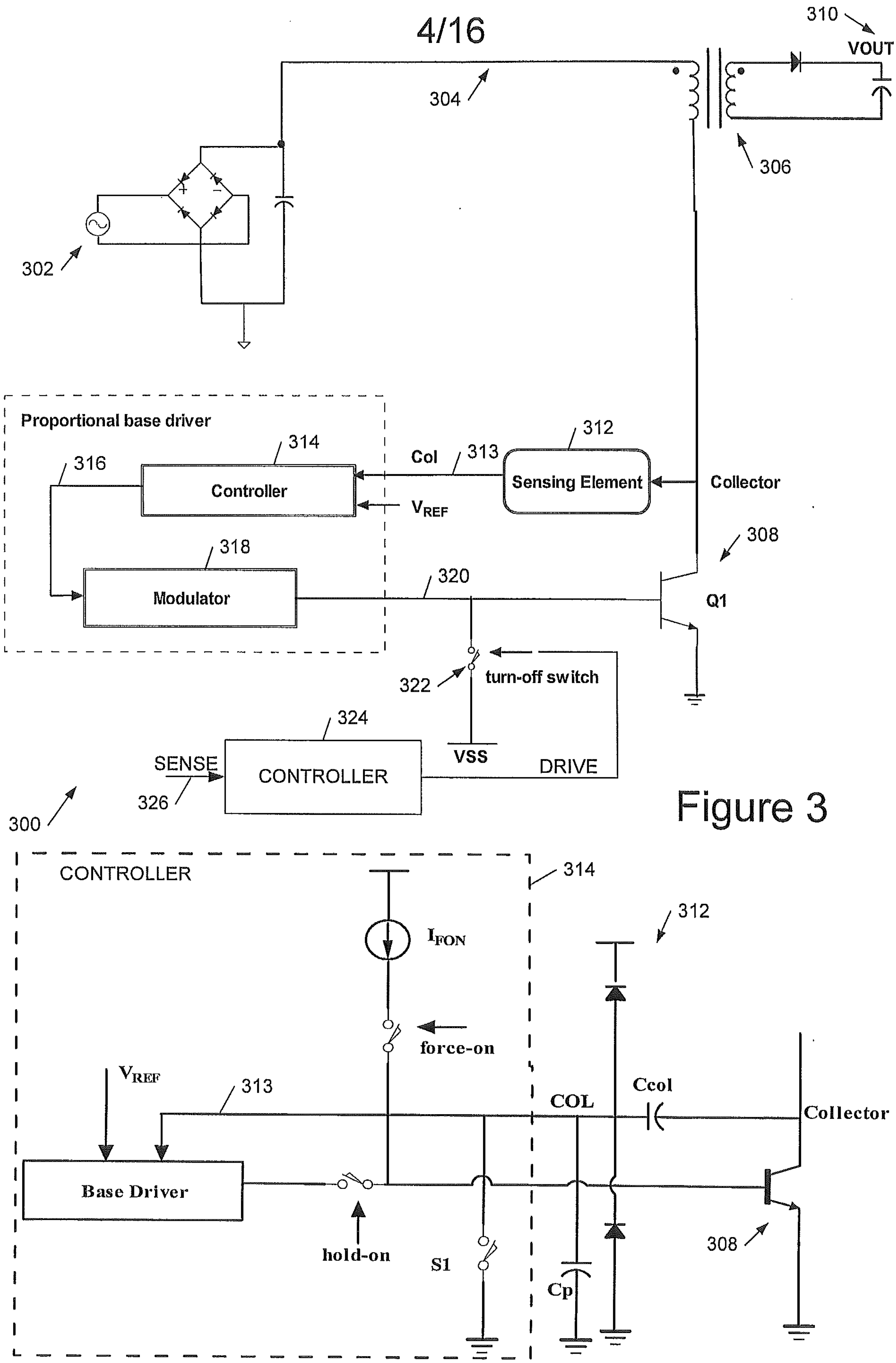
310
VOUT
304
306
302
Proportional base driver
314
316
Controller
Col
313
312
Sensing Element
Collector
$V_{REF}$
318
308
320
Modulator
Q1
322
turn-off switch
324
VSS
SENSE
CONTROLLER
DRIVE
326
300
CONTROLLER
314
312
$I_{FON}$
force-on
$V_{REF}$
313
COL
Ccol
Collector
Base Driver
hold-on
S1
Cp
308

Figure 3

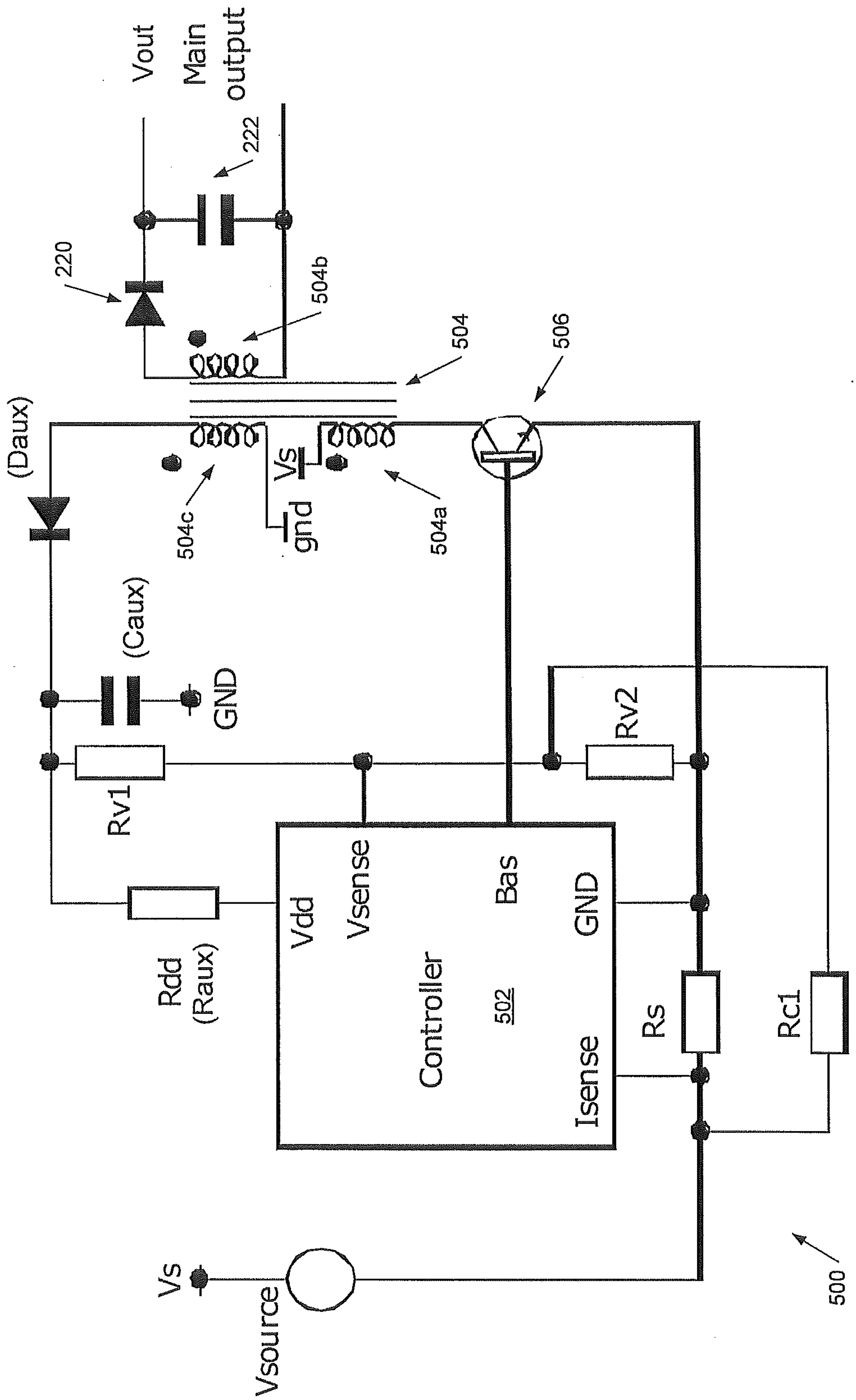
Vout
Main output
222
220
504b
504
506
(Daux)
504c
Vs
gnd
504a
(Caux)
GND
Rv1
Rv2
Rdd (Raux)
Vdd
Vsense
Bas
GND
Controller
502
Isense
Rs
Rc1
Vs
Vsource
500

Figure 5a

6/16

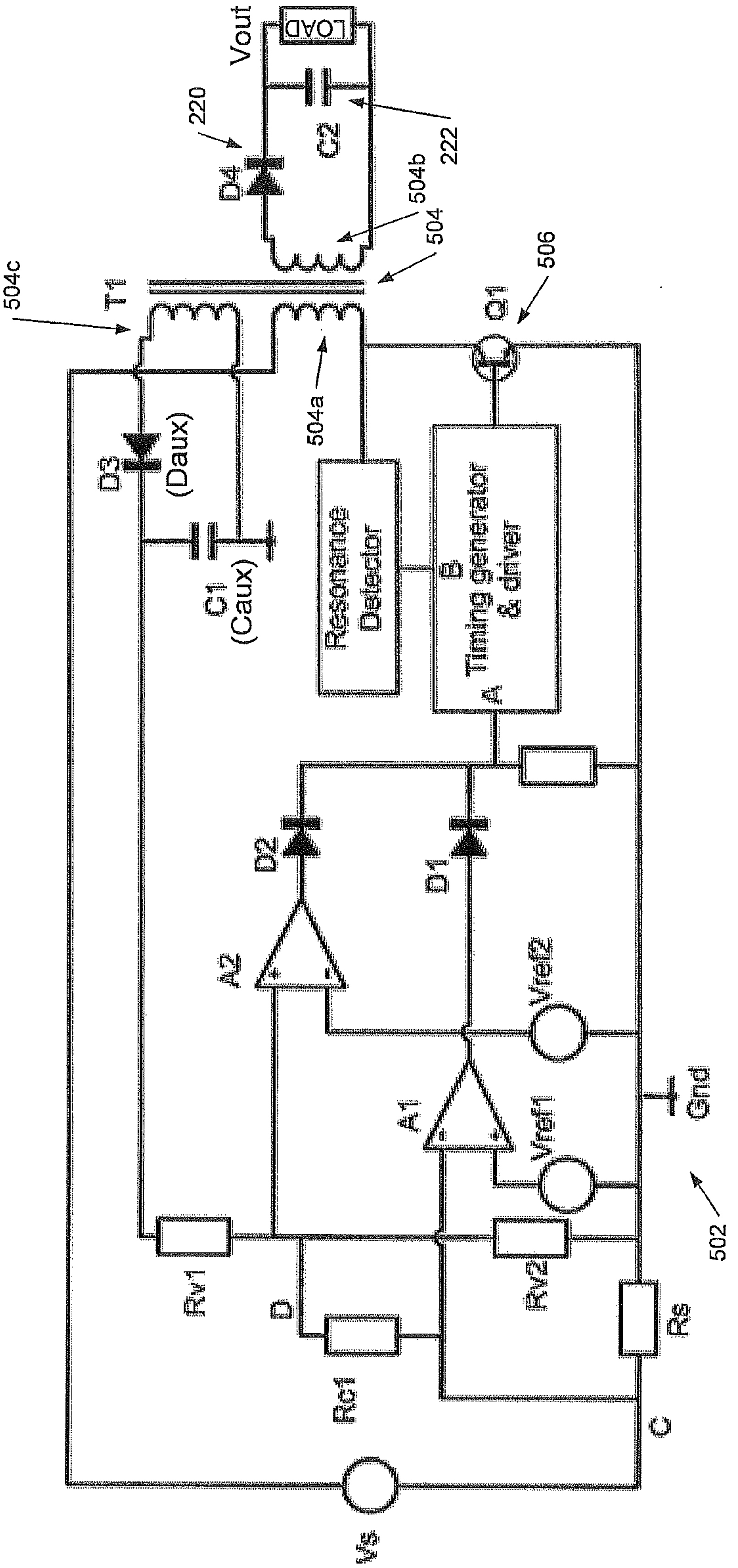


Figure 5b

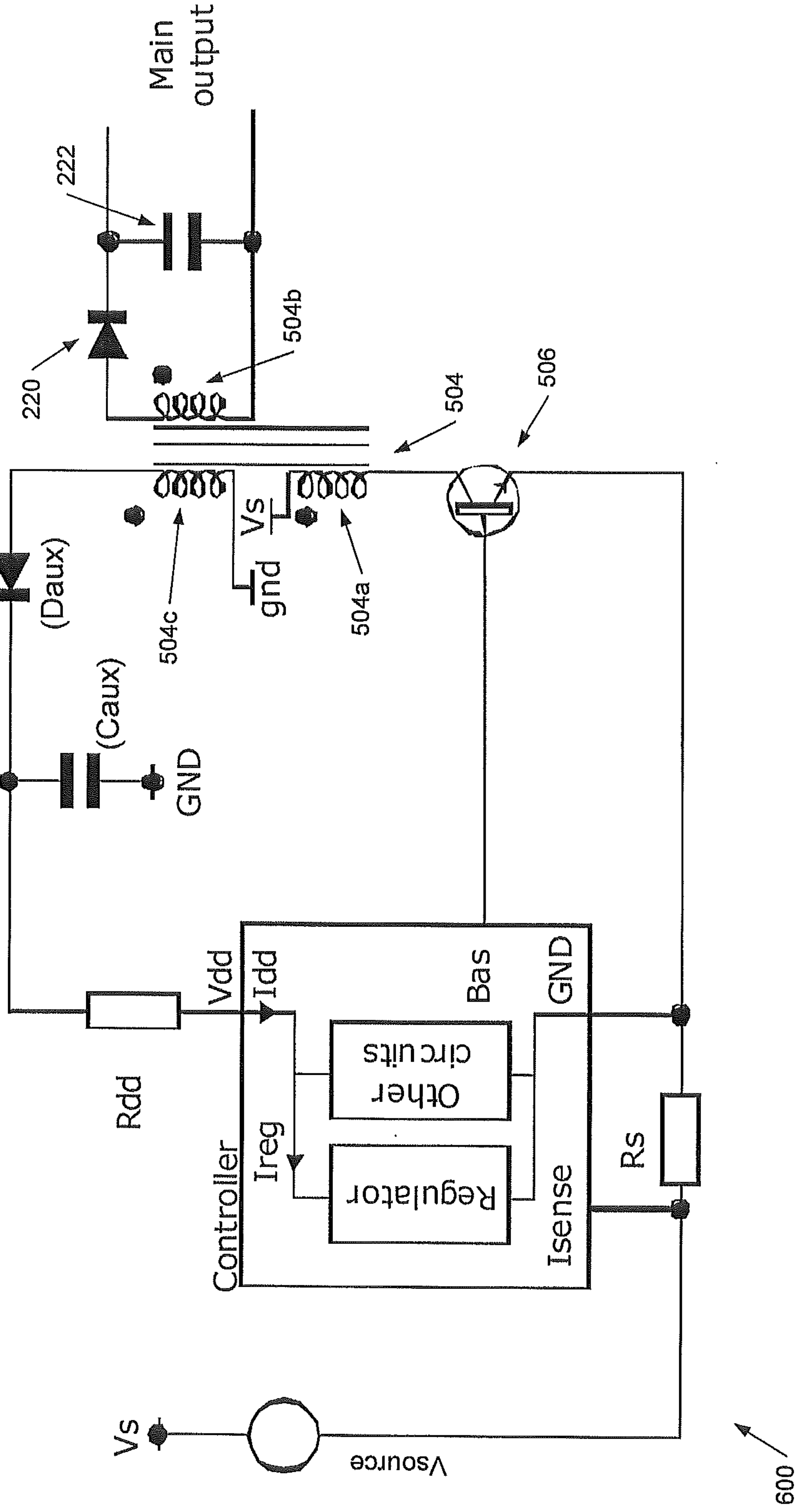
Main output
222
220
504b
504
506
(Daux)
504c
Vs
gnd
504a
(Caux)
GND
Vdd
Idd
Bas
GND
Other circ uits
Rdd
Controller
Ireg
Regulator
Isense
Rs
Vs
Vsource
600

Figure 6

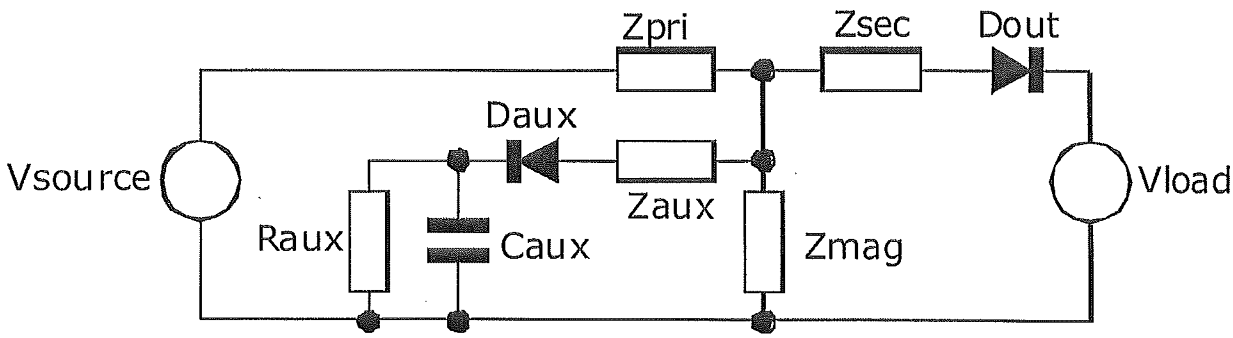


Figure 4

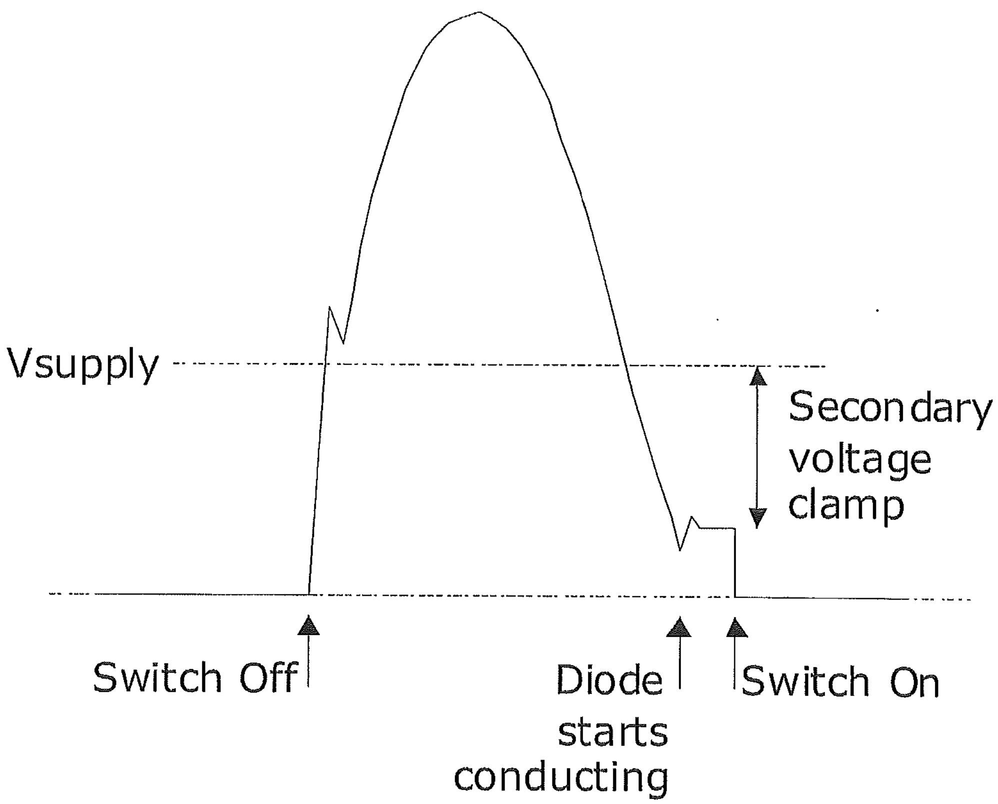


Figure 7a

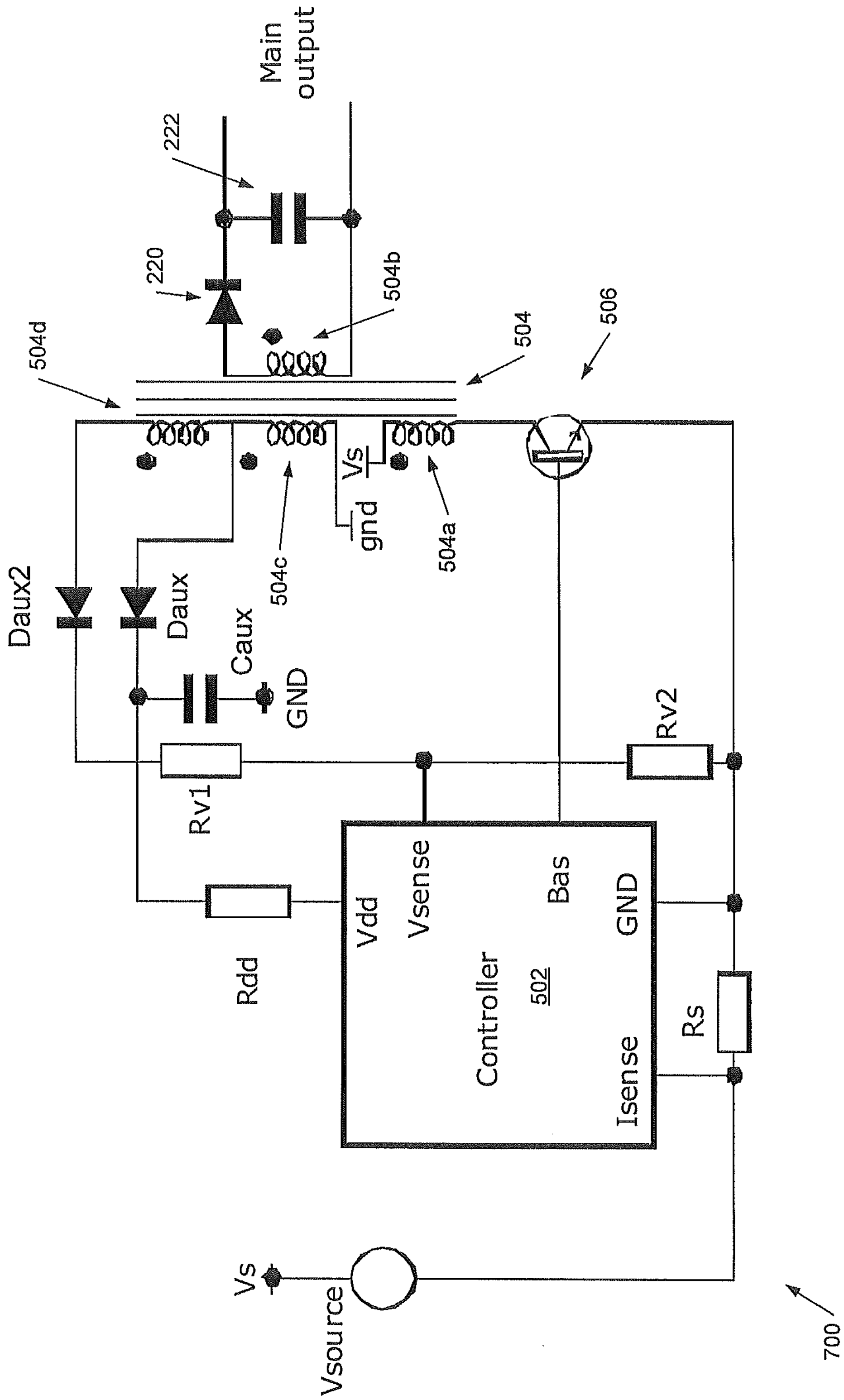
Main output
222
220
504b
504d
504
506
Vs
gnd
504c
504a
Daux2
Daux
Caux
GND
Rv1
Rv2
Rdd
Vdd
Vsense
Bas
GND
Controller
502
Isense
Rs
Vs
Vsource
700

Figure 7b

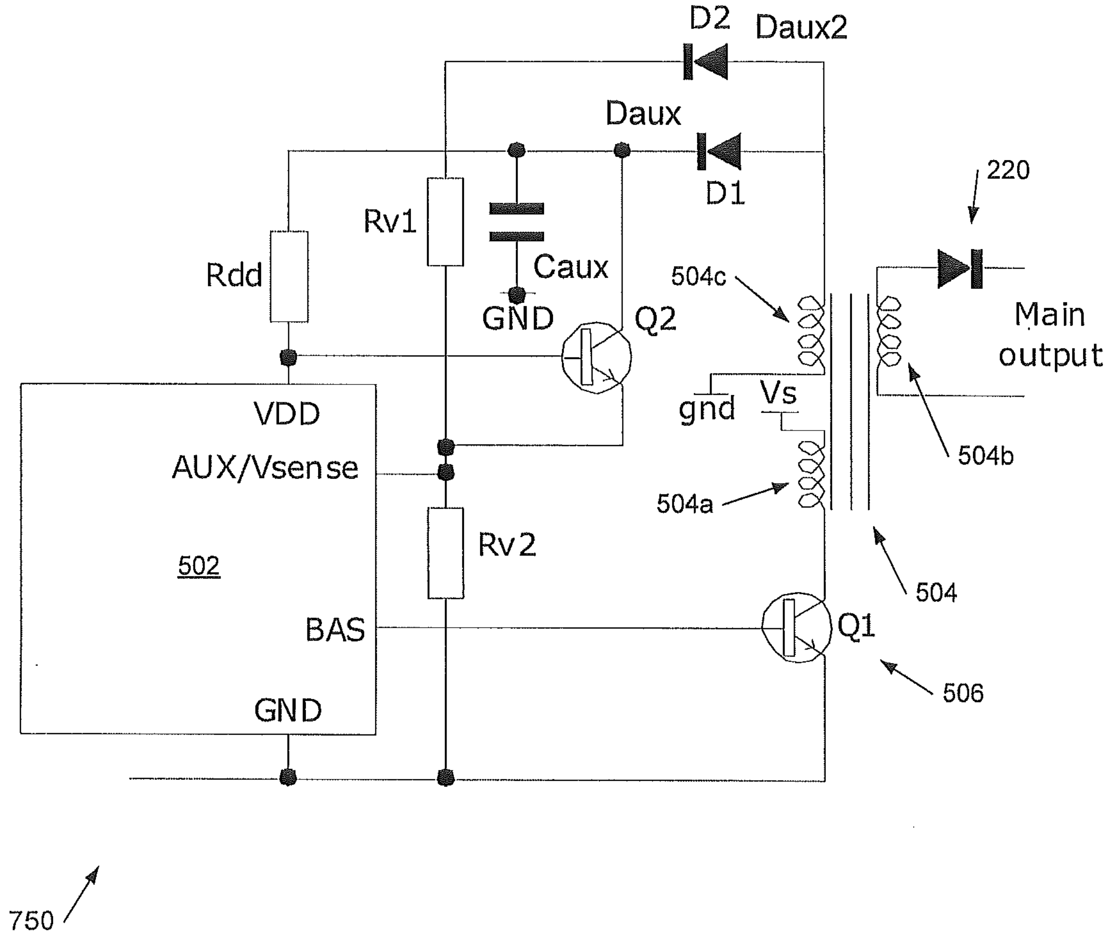
D2
Daux2
Daux
D1
220
Rv1
Rdd
Caux
504c
GND
Q2
Main
output
gnd
Vs
VDD
AUX/Vsense
504b
504a
Rv2
502
504
BAS
Q1
506
GND
750

Figure 7c

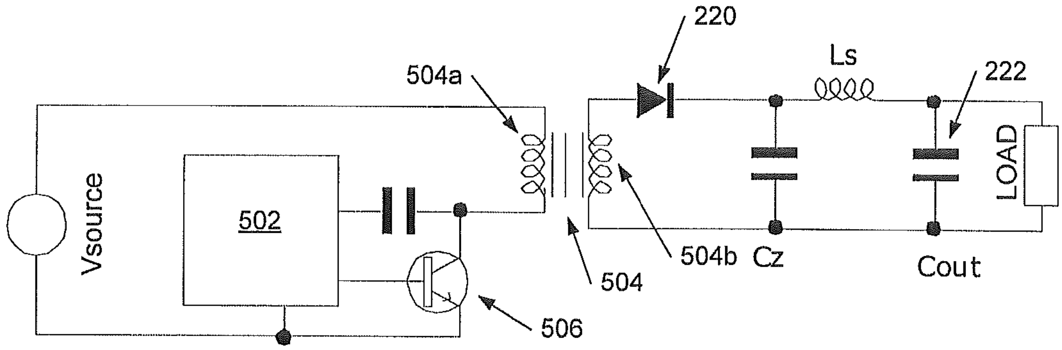


Figure 8a

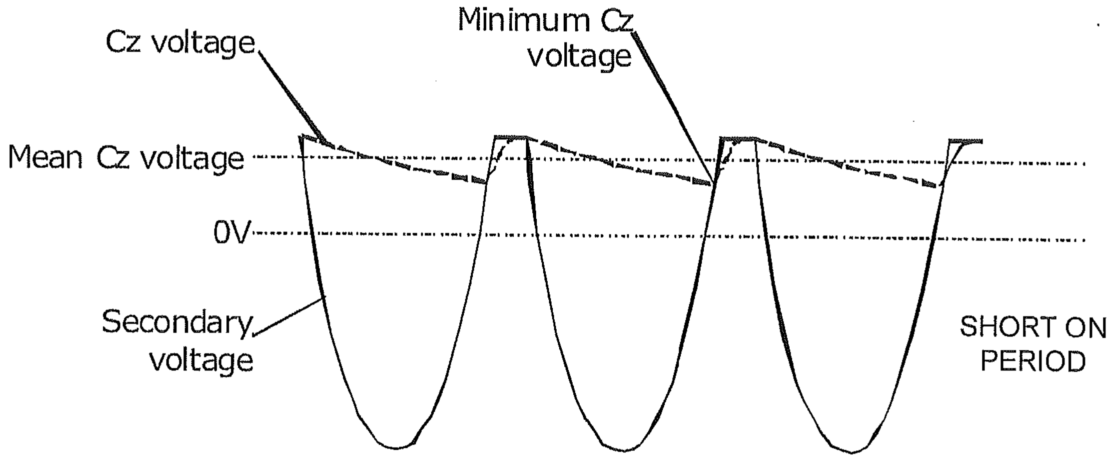


Figure 8b

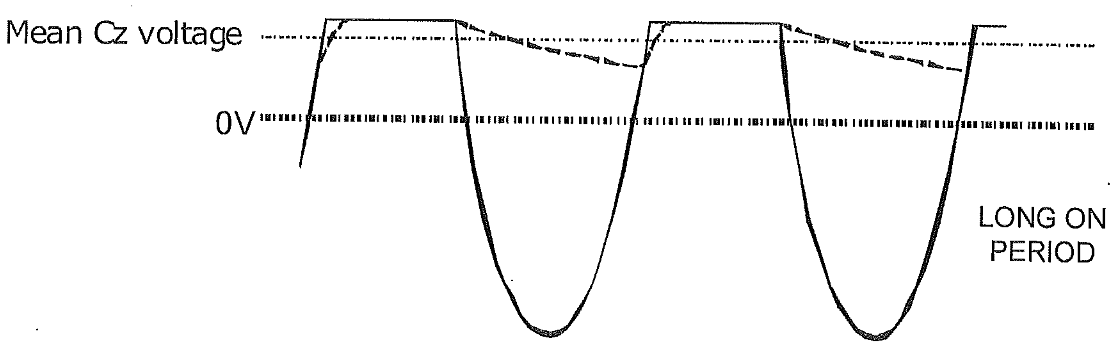


Figure 8c

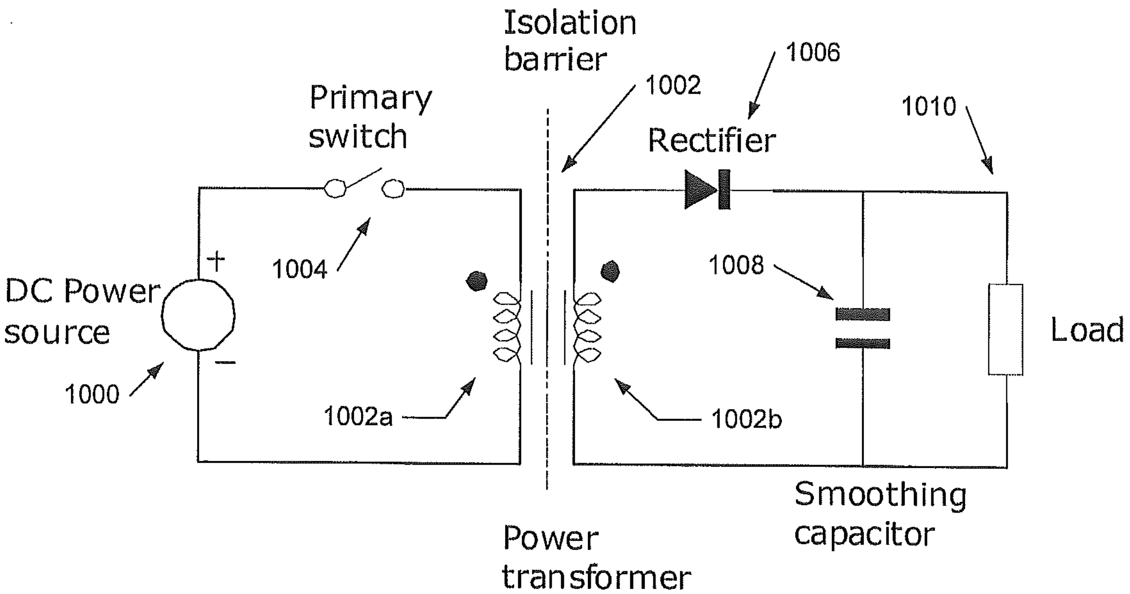


Figure 9a

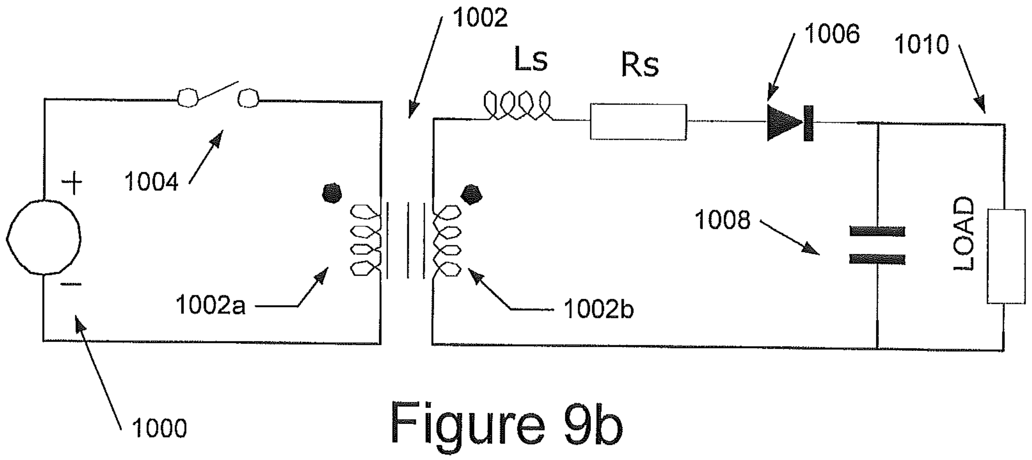


Figure 9b

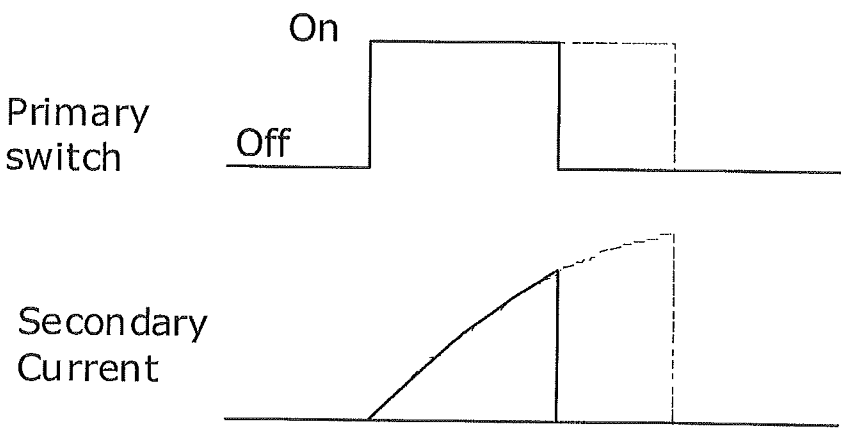


Figure 9c

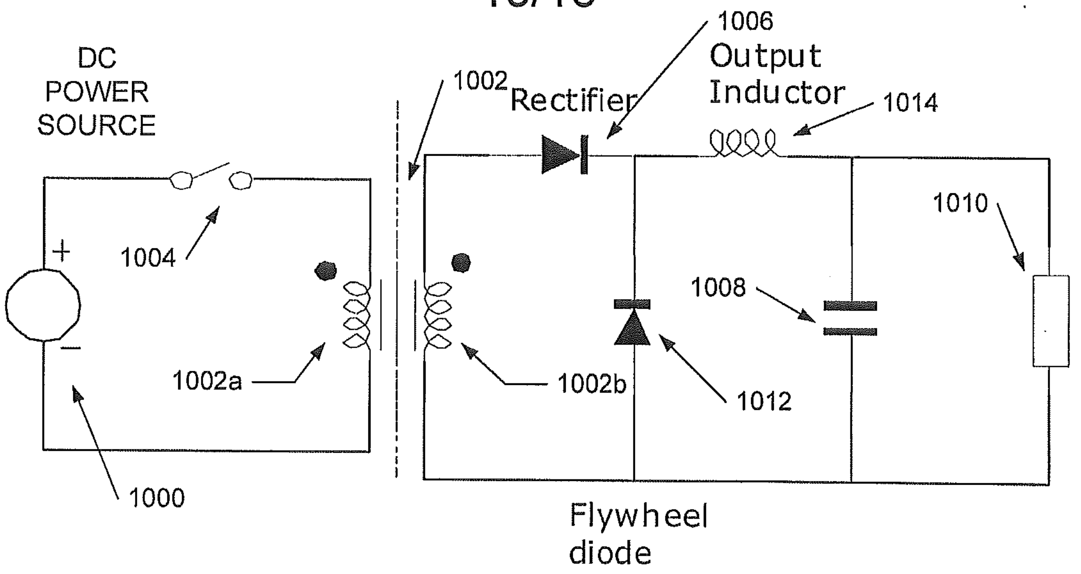


Figure 10a

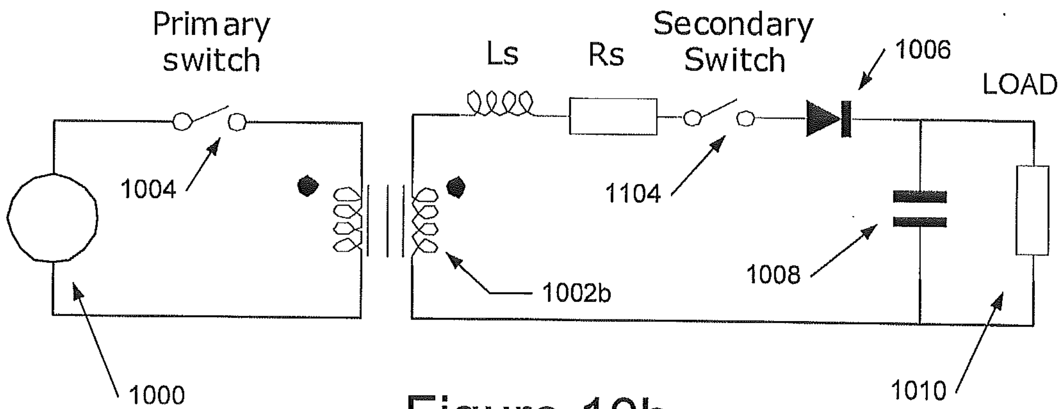


Figure 10b

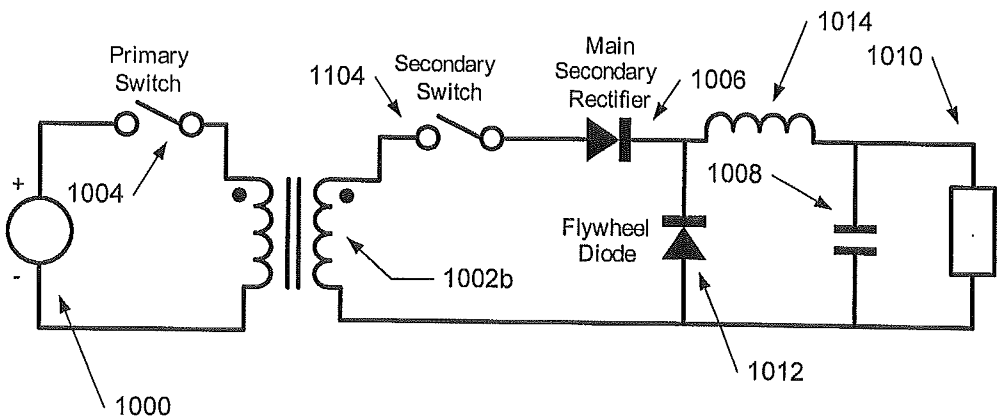


Figure 10c

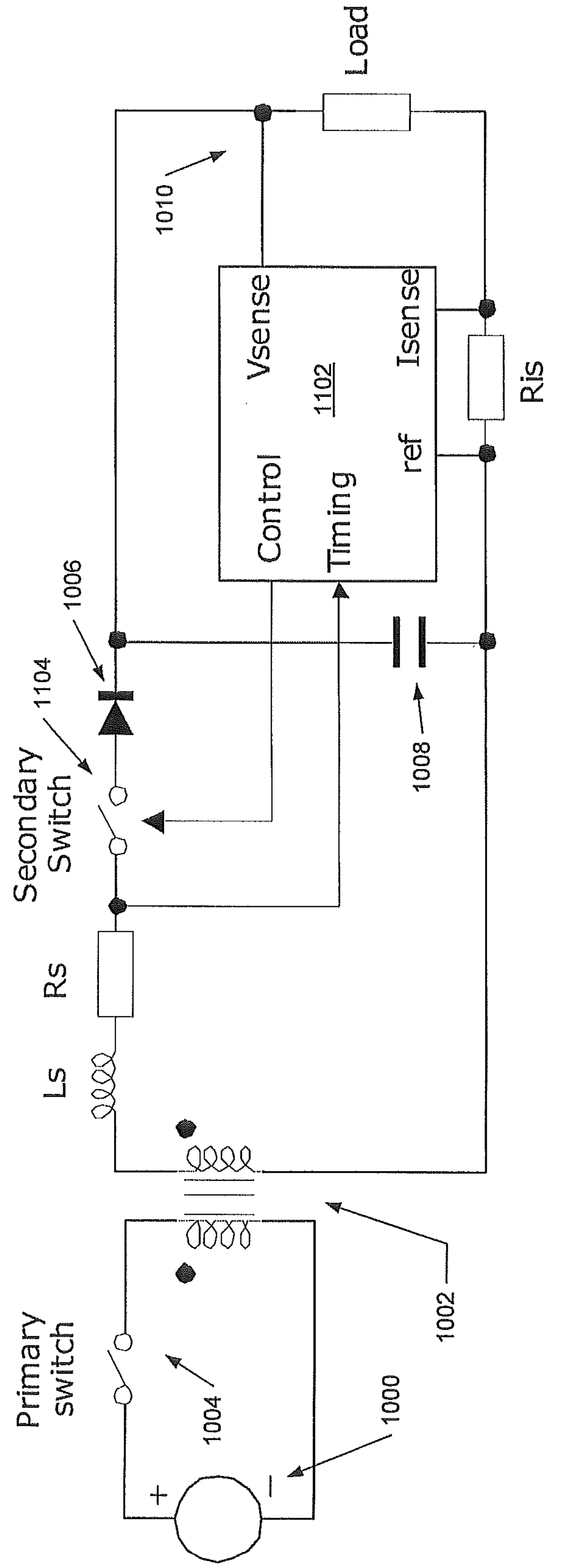
Load
1010
Vsense
1102
Isense
Ris
ref
Control
Timing
1006
1104
Secondary Switch
1008
Rs
Ls
Primary switch
1004
1002
1000
+
–

Figure 11a

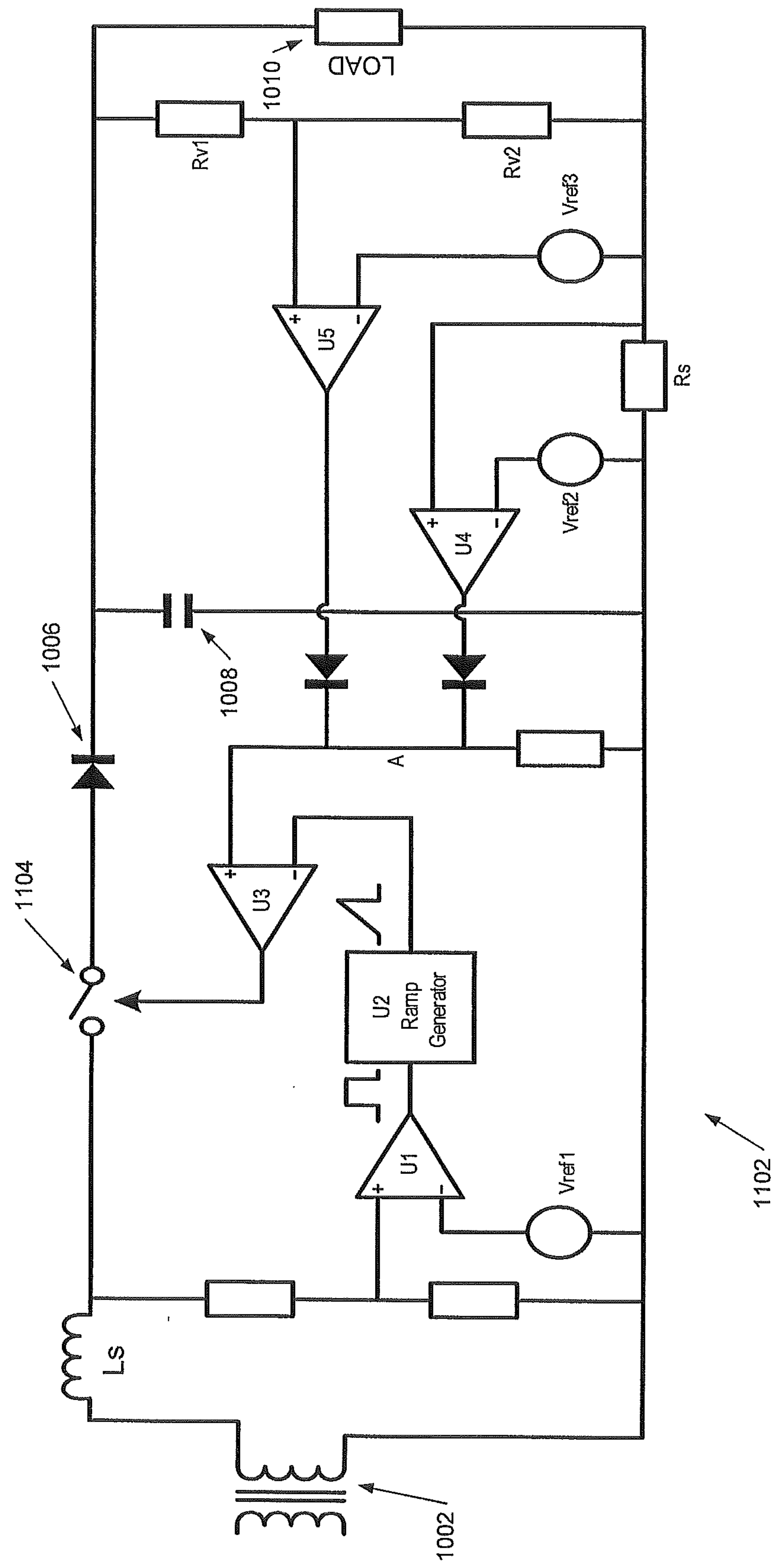
LOAD
1010
Rv1
Rv2
Vref3
U5
Rs
Vref2
U4
1006
1008
A
1104
U3
U2
Ramp
Generator
U1
Vref1
1102
Ls
1002

Figure 11b

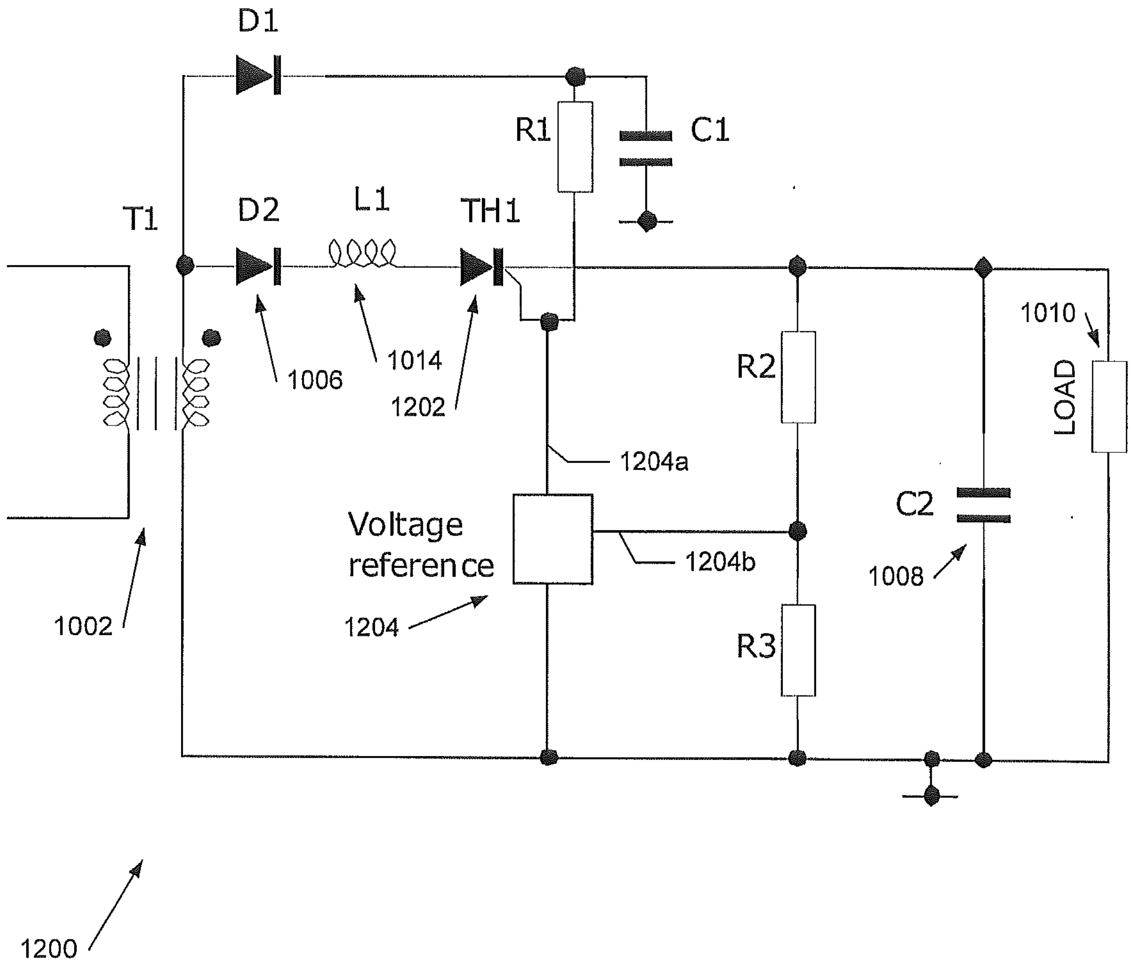
D1
R1
C1
T1
D2
L1
TH1
1006
1014
1202
1010
R2
LOAD
1204a
C2
Voltage
reference
1204b
1008
1002
1204
R3
1200

Figure 12