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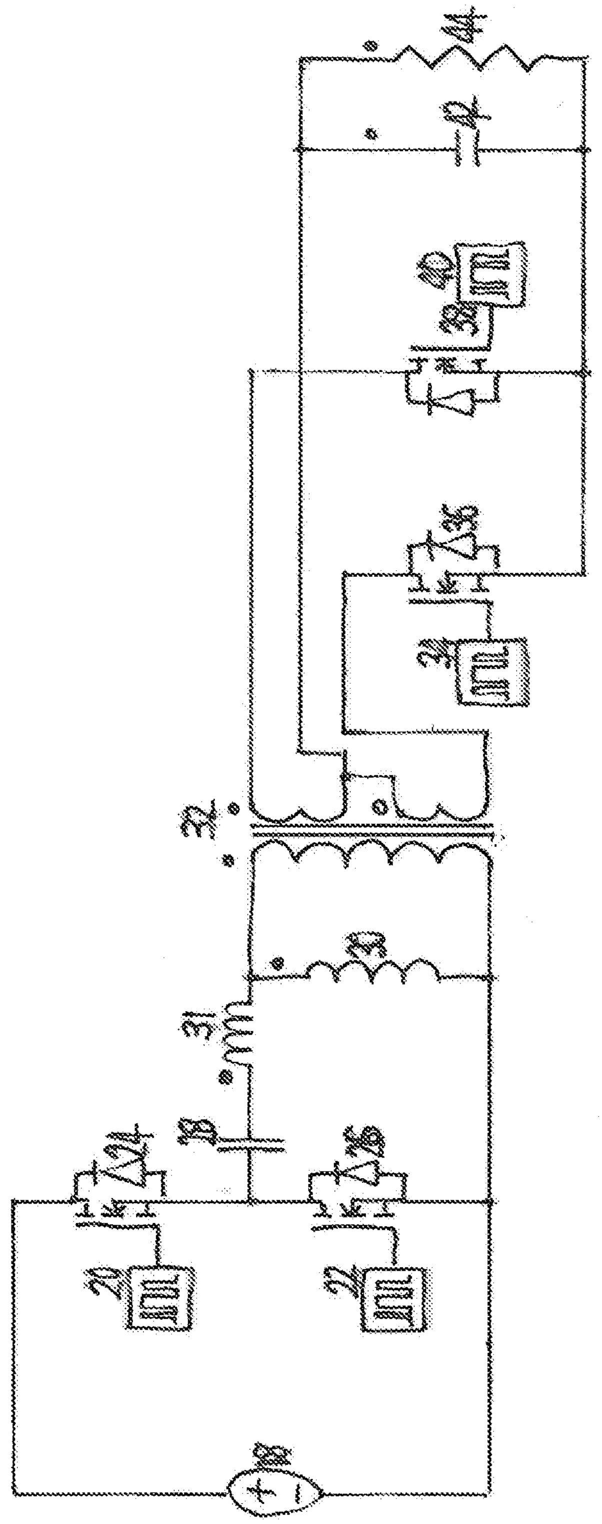
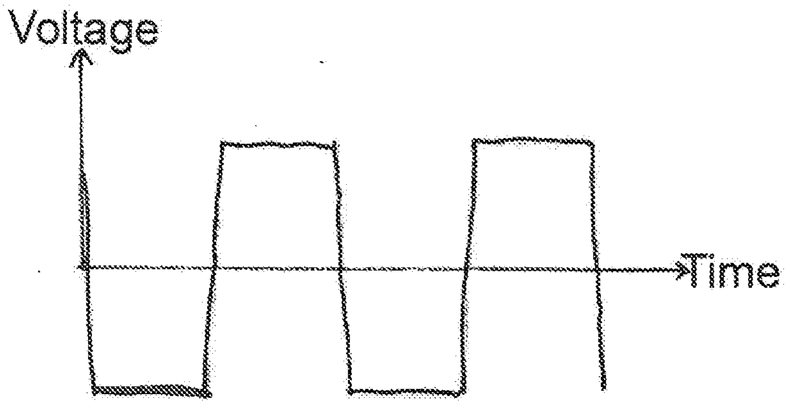
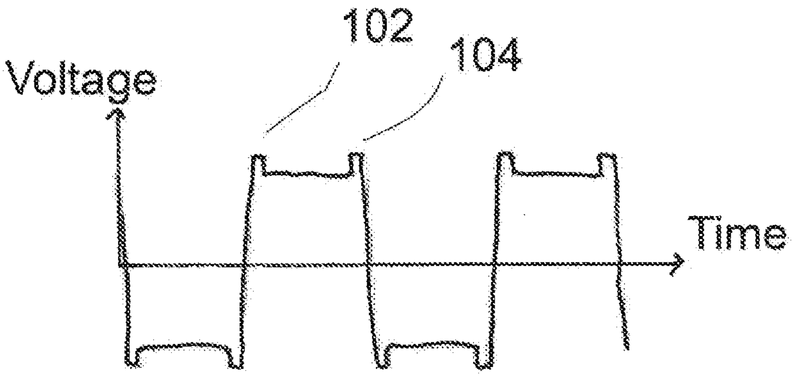


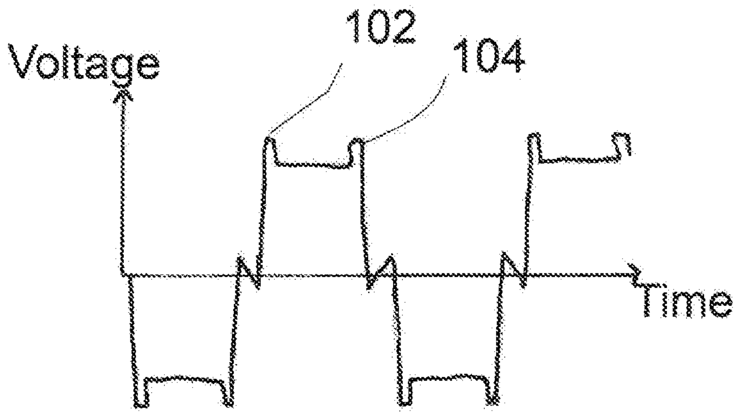
Figure 1



(a)



(b)



(c)

Figure 2

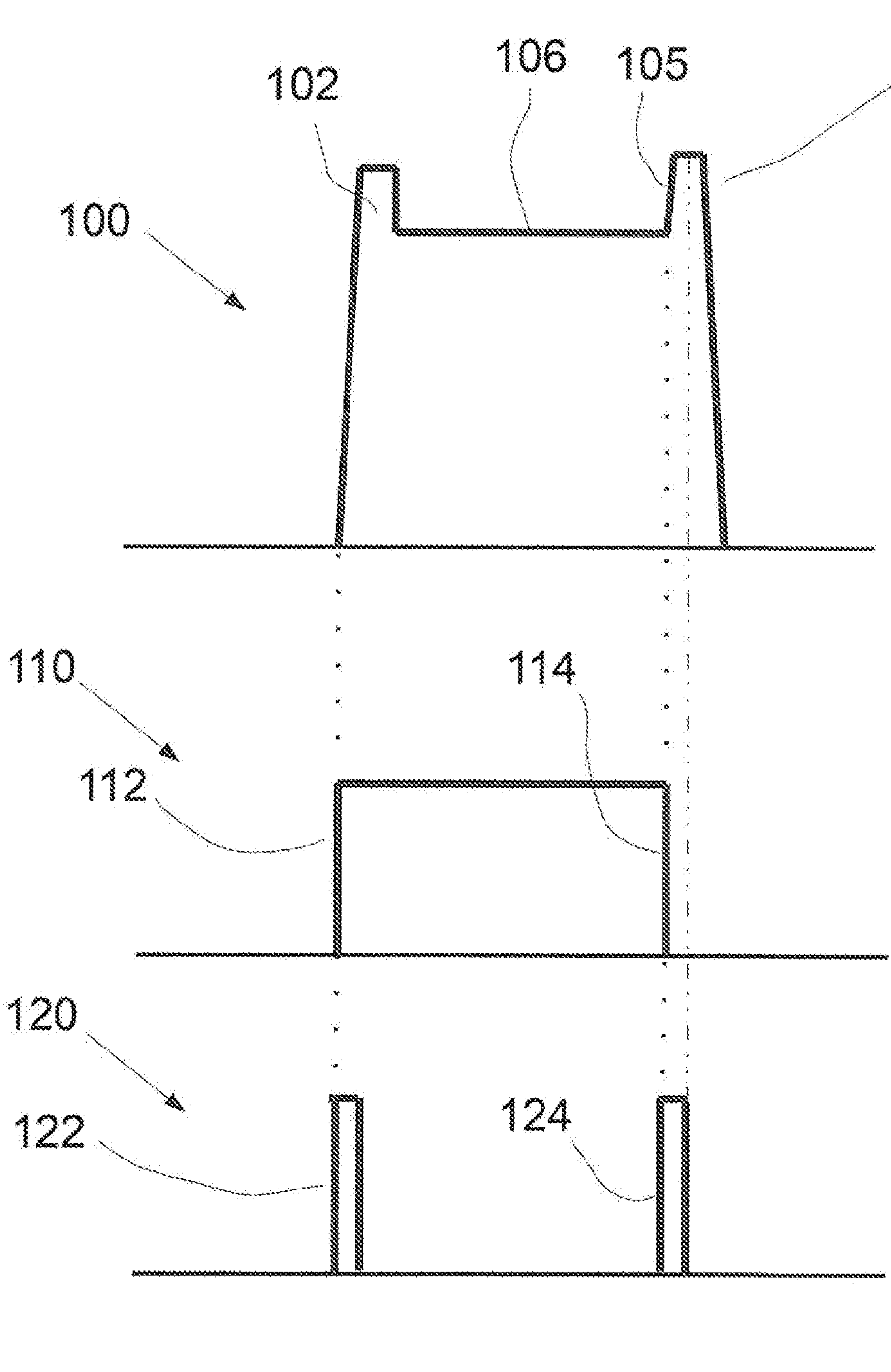


Figure 3

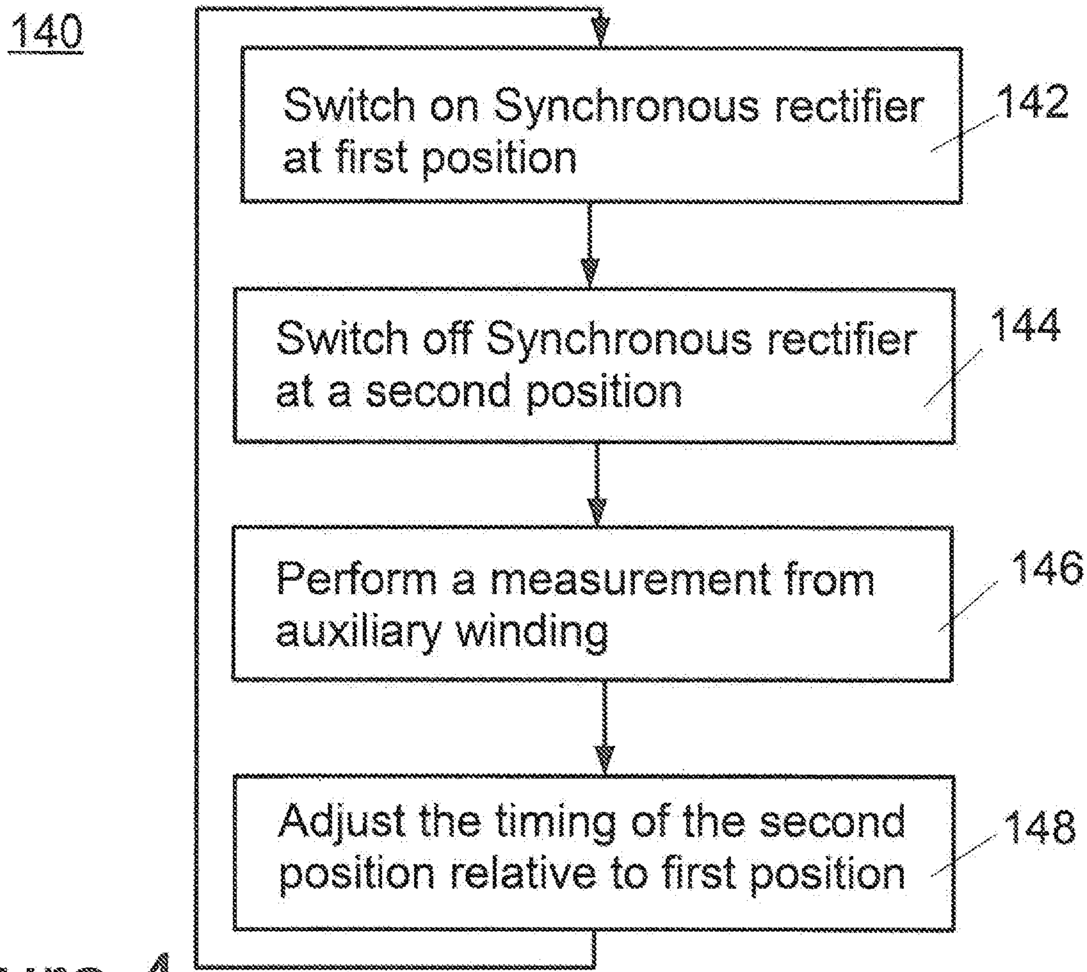


Figure 4

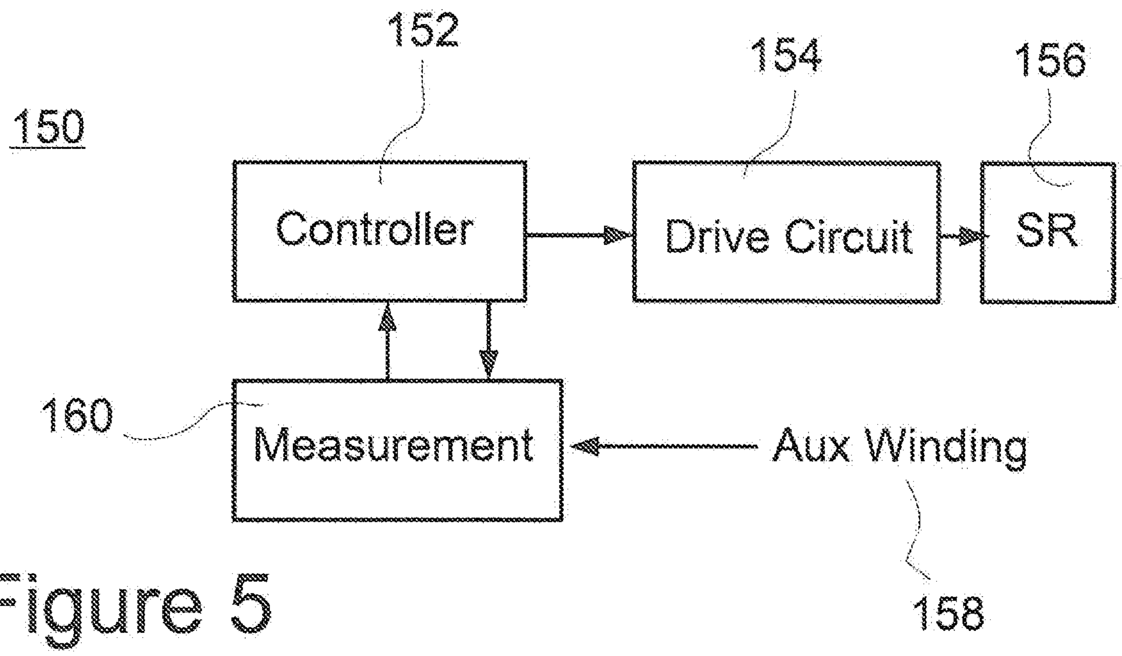


Figure 5

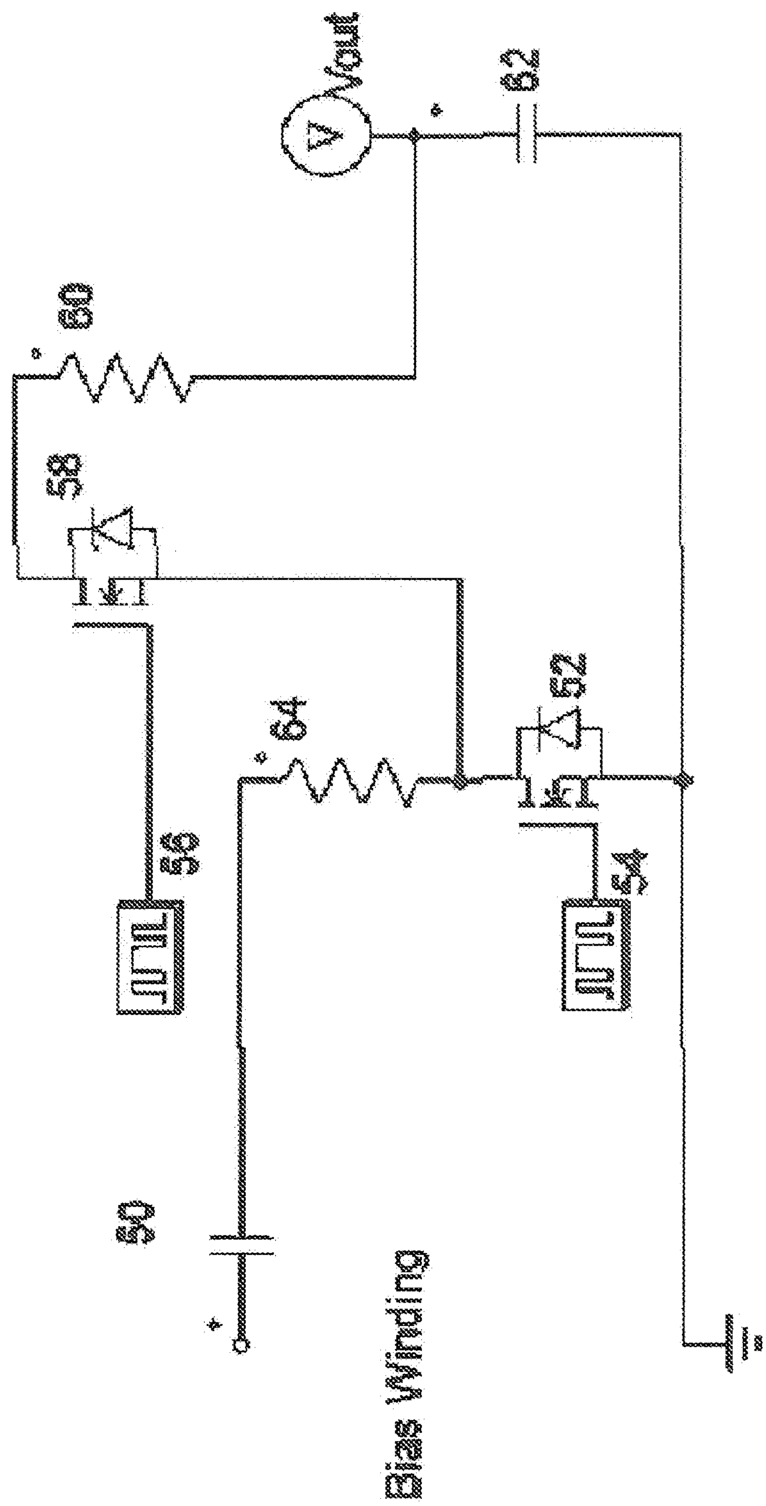


Figure 6

A PRIMARY SIDE METHOD OF CONTROL FOR SYNCHRONOUS RECTIFIERS

Field of the Application

The present application relates to the field of switching power supplies and in particular to switching power supplies in which a primary side is isolated from the secondary side and in which a synchronous rectifier on the secondary side is controlled from the primary side.

Background of the Application

In isolated switching supplies the general principle is that a primary side voltage is switched through a winding on the primary side of a transformer. One or more rectifiers are employed at the secondary side of the transformer in the provision of an output voltage. Whilst a variety of different topologies are known including Flyback, LLC and Forward converters, the general principle remains.

There is always a general desire to improve the efficiency of switching supplies. The use of a conventional p-n junction diode as a rectifier causes a power loss in the diode arising from a voltage drop across the diode of anywhere between 0.7 V and 1.7 V. This can be improved upon using Schottky diodes which exhibit lower voltage drops (as low as 0.3 volts).

However, further improvements are possible using a synchronous rectifier in which the diode is replaced by an actively controlled switching element such as a MOSFET. The actively controlled switch is switched so as to be on during the same time period that a diode would have inherently switched on. Active switching devices such as MOSFETs have a very low on-resistance meaning a reduction in power loss and a gain in efficiency.

However a known difficulty with using actively controlled switches such as MOSFETs is that the timing for controlling the switch is important to ensure efficient operation. Turning off a switch too early may result in body diode conduction and turning off the switch too late may result in negative current flow. In both of these cases, losses increase. At the same time, it is desirable to control the switch from the primary side since the synchronous nature is generally linked with the operation of one or more switches on the primary side.

To address this issue, various secondary-side “local” control approaches have been used, principally based around current sensing in the rectifier element. Disadvantages associated with these approaches include sensing difficulties in terms of timing and in terms of power loss.

The present application seeks to provide a primary side method of control for a secondary side synchronous rectifier.

Summary

Accordingly a first aspect of the present application provides a method of controlling a synchronous rectifier in a switching power supply as set forth generally in claim 1.

A second aspect provides a controller in accordance generally with claim 11. Advantageous embodiments are set forth in the dependent claims.

These and other features will be better understood with reference to the following which are provided to assist in an understanding of the teaching of the benefits derived from the present invention but are not to be construed as limiting in any fashion.

Description of Drawings

The present application will now be described with reference to the accompanying drawings in which:

Figure 1 illustrates a known LLC converter employing synchronous rectifiers;

Figure 2 illustrates exemplary waveforms that may be observed in the LLC converter of Figure 1;

Figure 3 is an enlarged view of a portion of a waveform of illustrated in Figure 2 and the associated exemplary switching signals;

Figure 4 illustrates a method according to an aspect of the present application;

Figure 5 shows a control arrangement according to a further aspect of the present application; and

Figure 6 shows a measurement circuit according to another aspect of the present application.

Detailed Description

The application will now be described with reference to an exemplary switching converter, and more particularly an LLC resonant converter. The LLC converter is used in switching converters which include a power factor correction deployment, typically between a capacitor fed from a power-factor correction stage and the load.

The operation of the circuit is well known and would be familiar to those skilled in the art. In brief, as shown in Figure 1, two primary side switches 24 and 26 are operated as a symmetric half-bridge with nominally 50:50 drive ratio. A small dead-time is generally introduced to allow current to drive the drain voltage of the switch that is about to conduct to zero.

The output from the symmetric half bridge is connected to a capacitor 28 which in turn is connected to and drives an inductor/transformer assembly 31, 30 and 32. The inductor/transformer assembly comprises an inductor 31 which is in series with the capacitor and the parallel combination of magnetising inductor 30 and the primary winding of transformer 32. The individual elements 30, 31 and 32 may be provided discretely although frequently they are combined into one magnetic element. These elements give rise to a series resonant frequency determined by the values of capacitor 28 and inductor 31 and a parallel resonance determined by including the magnetising inductor 30.

A number of variations in this circuit are possible. For example, the capacitor 28 may consist of two capacitors connected one to each rail, and the inductor 32 may have a single secondary winding used with a voltage doubler or full-bridge rectifier configuration rather than the half-bridge shown.

Synchronous rectifiers 36 and 38 are driven by signals from drivers 34 and 40 respectively, feeding an output capacitance 42 and load 44. The drive signals are such that each synchronous rectifier is turned on generally in synchronisation with the appropriate primary switch. If the converter is operated at or above series resonance (as determined by 28 and 31), the synchronous rectifier is switched off substantially at the same time as the corresponding primary switch.

The optimal operating condition for a converter of this type is often in the frequency range just below the series-resonant frequency. If diodes were used for rectifiers 36 and 38, these would inherently turn off under benign zero-current conditions. As explained in the background, when controlled synchronous rectifiers are used, it is desirable to turn these off under close to zero-current conditions also. Turning off the switch too early will result in body diode conduction and turning off the switch too late will result in negative current flow. In both these cases, losses increase.

It will be recognised that there are essentially two alternative types of control applied to LLC resonant converters of this type, with each type described as follows.

The first type of control involves feedback of voltage from the secondary side, with the main control loop used to adjust the frequency. This in turn affects the gain or voltage conversion ratio of the converter, and frequency can be adjusted such that the desired output voltage is obtained. The control task for a minor loop associated with efficiency optimisation relates to the relative timing of turn-off of the synchronous rectifiers. Typically a minimum value for synchronous rectifier conduction time is established based on knowledge of circuit parameters, and the minor loop optimises timing to accommodate component tolerances, age effects and second-order effects associated with different operating conditions. The minor control loop then extends this timing to minimise body diode conduction subject to the limitation that reverse current does not flow. Typically the minor loop will operate an order of magnitude slower than the main control loop. Minor loop may be controlled based on the method of body diode conduction measurement described below.

In the second type of control, the goal is to have open-loop (i.e. no voltage feedback from the output) operation at series-resonance such that a quasi-fixed transformation ratio is obtained, and this condition can be detected by sensing the point between body diode conduction and negative current flow conditions in synchronous rectifier elements. The turn-off drive for the synchronous rectifiers is in the mode synchronised with the turn-off of the primary switches, and thus the frequency of the converter can be adjusted based on detection of this point for synchronous rectifier operation. The converter here will typically be designed such that the gain-frequency curve is relatively flat in the calculated operating range and the control can thus be regarded as a low background-mode efficiency optimisation. As with the first type of control, the second type of control may also be performed based on the method of body diode conduction measurement described below.

Controllers for switching LLC converters or indeed any switching converter can benefit from primary-side control, with synchronous rectifier control provided centrally from a controller on the primary side with gate drive signals provided effectively, economically and with excellent timing accuracy.

The present application is directed towards providing a method by which the transition conditions between body-diode conduction and negative current flow may be measured on the primary side.

To perform this, the present application uses an indirect measure of secondary side values by using an auxiliary winding on the transformer. The output from this auxiliary winding is provided to the primary-side controller which in turn derives secondary side measurements. The auxiliary winding may be provided as a separate winding with no other function or it may for example have another function, for example to provide a bias supply to the primary-side controller. Although, depending on the implementation this may not be practical, since for example the bias supply may be loaded excessively by diode pulse currents. In such a circumstance a separate sense winding is desirable for the auxiliary winding.

The mode of operation of the present application will now be described with reference to some exemplary waveforms as might be produced from an auxiliary winding.

The voltage waveform across such a winding in an “ideal” condition (at or above series resonance) may be as shown in figure 2(a). However, in a practical case, the waveform is likely to have “ears” as in shown figure 2(b). Similarly, it may appear as shown in figure 2(c), corresponding also to a condition where the converter is operated below the series resonant frequency.

The first “ear” after the transition from high-low or vide-versa typically represents some practical issues associated with ensuring precise timing associated with the switch-on of the synchronous rectifier as may be seen from Figure 3 in which an exemplary switching waveform 110 for a half switching cycle is shown with the corresponding measurement 100 from the auxiliary winding. More particularly, the synchronous rectifier starts to turn on at a first position corresponding with the rising edge 112 of the switching waveform. The switch-on “ear” 102 is typically quite short and may be associated with a condition of low current flow on the secondary side (i.e. the losses associated with this are relatively small). Parasitic ringing effects may also contribute to the appearance of a small spike. This waveform aspect is however not particularly relevant to considerations in this application.

It should be appreciated although not apparent from the exemplary figures that the first “ear” 102 at the point where the synchronous rectifier is turned on is not the same as the second “ear” 104 at the end of the conduction period.

The present application uses a measurement of the “ear” 104 that appears after the synchronous rectifier is switched off. The measurement of the “ear” is employed as an indication as to whether the synchronous rectifier timing is working correctly. This “ear” represents the voltage of the body diode of the synchronous rectifier reflected back through the auxiliary winding. It will be appreciated that the “ear” 104 appears in situations where the synchronous rectifier is turned off too early and the current continues to flow through the body diode of the synchronous rectifier. More particularly, the synchronous rectifier turns off at a second position corresponding with the falling edge 114 of the switching waveform. It will be understood that there may be a delay inherent in turning on, illustrated by the transition 105 prior to full body diode conduction, and turning off the synchronous rectifier. In the exemplary waveform of Figure 3, the current in the secondary winding continues to flow but does so through the body diode of the synchronous rectifier, which represents a loss.

Whilst a synchronous rectifier may be operated by a single waveform 110 with turn on effected by the rising edge and turn off effected by the falling edge, it is also known prior to full body diode conduction to use two separate pulses to operate a synchronous rectifier, as illustrated by waveforms 120, in which a first pulse 122 might be used to turn on the synchronous rectifier with a second pulse 124 employed to switch off the synchronous rectifier. Thus the reference to first position and second position being controlled may be taken to refer to the rising and falling edges of the single pulse 110 or the position (notionally rising edges) of the first and second pulses 122, 124.

The present application operates from the premise that regardless of whether a single pulse or dual pulses are used to operate the synchronous rectifier, the synchronous rectifier drive timing relative to the primary switching instants should be adjusted so as to minimise the width of the “ear” that appears at the end of the conduction period. Alternatively stated, the position where the synchronous rectifier is turned on should be adjusted with the position where the synchronous rectifier is turned off so as to minimise body conduction losses of the synchronous rectifier.

More particularly, a method is provided which seeks to perform a measurement with respect to the second “ear”. The measurement may be used in a controller controlling the synchronous rectifier to adjust the timing of the second position with respect to the first position. In greater detail, and with reference to the process flow 140 of Figure 4 and the control arrangement 150 of Figure 5, a controller 152 which is provided on the primary side of the transformer of a switching supply generates 142 a signal at a first position in a switching cycle to turn on a synchronous rectifier. For ease of illustration the controller is shown simply as operating a single synchronous rectifier. As the controller is provided on the primary side, a drive circuit 154 is employed to provide a drive signal to the synchronous rectifier 156 on the secondary side. In the case of a single pulse such as pulse 110 in Figure 3, the drive circuit may simply comprise a small transformer. The drive circuit may be more complicated, for example when the two-pulse 120 mode of operation is employed and in which case two transformers are generally required with the first for turning on and the second for turning off the synchronous rectifier.

The controller causes the synchronous rectifier through the drive circuit 154 to turn off at a second position in the switching cycle of the switching power supply. A measurement circuit 160 obtains 146 a measurement from an auxiliary winding of the transformer at a position shortly after the second position. More particularly, the measurement circuit receives a signal from the controller and uses this signal to determine a position to perform a measurement. The determined position may be set using a predetermined delay which is relatively short compared to the duration of the switching cycle, for example in the range of 1/100 to 1/10,000 the duration of the switching cycle. Where there are two separate pulses for turning on and turning off the Synchronous rectifier, the falling edge of the pulse employed to turn off the synchronous rectifier may be advantageously employed. The measurement obtained is used to identify the presence of an “ear” (representing body diode conduction losses) or to provide a measure of the size of the conduction losses occurring. The controller having this measurement may operate in a variety of different ways depending on the particular control algorithm selected. The controller operates to effectively reduce body diode conduction losses in the synchronous rectifier by adjusting 148 the second position in a subsequent switching cycle based on a value derived from the obtained measurement. The derived value may be a series of values obtained from a plurality of switching cycles.

The method is generally concerned with the identifying and measurement of the size of the “ear” relative to the measurement 106 from the auxiliary winding when the synchronous rectifier is switched on. A difficulty with this is that the difference between the value of the “ear” voltage as presented by auxiliary winding and that value 106 presented when the synchronous rectifier is turned on may be relatively small and hence difficult to detect. Accordingly, subtracting out the earlier value allows for a more reliable measurement (since, in practise as will be explained below, it is the width rather than the amplitude of the “ear” that is important). An initial measurement may be obtained from the auxiliary winding at a point between the first and second positions. This measurement may be subtracted from the subsequent measurement for the “ear” to provide the derived value on which the controller operates. A convenient implementation of such an approach is discussed below in greater detail with respect to Figure 6. Alternatively, a predetermined value (representative of the expected output voltage reflected back through the auxiliary winding) may be employed or indeed a measurement of the output voltage obtained by another means may be employed (albeit adjusted to account for the ratio of turns between the auxiliary winding and the secondary winding).

A convenient measurement circuit and method for obtaining a smoothed voltage waveform proportional to the amplitude and duration of the “ear” will now be described with reference to Figure 6. However, in practice the amplitude is constant and effectively set as the reflected value of the body-diode conduction voltage which is typically around 1V for most silicon switches, or twice this if a full-bridge rectifier is used on the secondary side. Thus since the amplitude is going to be relatively constant, it is the measure of width that is more important for the minimisation of the width of the “ear”.

In the circuit, capacitor 50 functions with switch 52 analogous to a “DC restore” circuit. During the on-phase as determined by a control signal 54 from the controller of the converter, the capacitor charges up to the reflected output voltage as switch 52 is “on” during this phase. A resistor 64 may be provided in series with the capacitor to limit current in switch 52. A second switch 58 is operated in a complementary fashion to that of the first switch. The second switch may, for example where two pulse operation is employed as described above, be synchronously operated with the synchronous rectifier turn-off drive pulse. In this case, the complement of this drive signal may be used to drive switch 52. The voltage level of the “ear” above the reflected normal output voltage is thus captured in this fashion and integrated using resistor 60 and capacitor 62 to provide a measure to the controller.

This signal can thus be the key input to a control loop. This control loop can determine the synchronous rectifier turn-off timing relative to the primary side drive in the case of overall voltage feedback where the converter is operating below the series-resonant frequency or the minor loop described above. In the case of open-loop voltage operation, the control loop can control the frequency of operation.

It will be appreciated that whilst minimising diode body conduction losses is desirable, operating a switching power supply at the point where this occurs precisely may be extremely difficult without straying into a negative current flow situation. As will be appreciated by those skilled in the art, negative current flow situations are generally less desirable than diode body conduction losses. Accordingly, the controller may be set to operate about a predetermined minimum value of “ear” so as to limit the opportunity of negative flow conditions arising.

Thus for example, the control loop employed within the controller may be a linear PID-type. The controller may be selected to have a reference finite small value of body-diode conduction. Alternatively a digital approach may be used where the controller periodically shortens the drive period for the synchronous rectifier to provoke an “ear” condition and then “backs off” by increasing the drive period slightly.

The method the present application may be employed with a variety of different switching topologies using a transformer including for example but not limited to Flyback and LLC converters.

Claims

1. A method of controlling a synchronous rectifier in a switching power supply comprising a transformer with a primary side winding and a secondary side winding, where the synchronous rectifier is on the secondary side, the method comprising using a controller on the primary side to perform the steps of:
operating the synchronous rectifier to turn on at a first position and to turn off at a second position in a switching cycle of the switching power supply;
obtaining a measurement from an auxiliary winding of the transformer at a position after the second position;
adjusting the second position in a subsequent switching cycle based on a value derived from the obtained measurement.

2. A method according to claim 1, wherein the step of operating the synchronous rectifier to turn on at a first position and to turn off at a second position in a switching cycle comprises providing a switching pulse with turn on effected at the start of the pulse and turn off effected by the end of the pulse.

3. A method according to claim 1, wherein the step of operating the synchronous rectifier to turn on at a first position comprises providing a first pulse at the first position and wherein a second pulse is employed to turn off the switch at the second position.

4. A method according to any preceding claim wherein the value derived is the obtained measurement less a second value.

5. A method according to claim 4, wherein the second value is a value representative of the output voltage on the secondary side as reflected back through the auxiliary winding.

6. A method according to claim 4 or claim 5, wherein the second value is obtained by a measurement from an auxiliary winding of the transformer at a position before the

second position.

7. A method according to any one of claims 4 to 6, wherein the measurement is provided to a control function which in turn provides a control output to adjusts the second position.

8. A method according to claim 7, wherein the control function seeks to minimise the measurement value over time.

9. A method according to any preceding claim, wherein the measurement is an instantaneous measurement.

10. A method according to any one of claims 1 to 8, wherein the measurement comprises an aggregated measurement obtained during a sampling period.

11. A controller for operating a synchronous rectifier in a switching power supply comprising a transformer with a primary side winding and a secondary side winding, the controller being configured to operate from the primary side of the transformer and to provide a first signal to cause the synchronous rectifier to turn on at a first position and to provide a second signal to turn off the synchronous rectifier at a second position in a switching cycle of the switching power supply;
the controller being configured to receive a measurement from an auxiliary winding of the transformer at a position after the second position and where the controller adjusts the second position in a subsequent switching cycle based on a value derived from the obtained measurement.

12. A controller according to claim 11, wherein the first and second signal are the same pulse with turn on effected at the start of the pulse and turn off effected by the end of the pulse.

13. A controller according to claim 11, wherein the first and second signals are separate pulses.

14. A controller according to any one of claims 11 to 13 further comprising a measurement circuit for connection to the auxiliary winding and for providing the measurement to the controller.

15. A controller according to claim 14, wherein the measurement circuit provides a measure relative to a measurement obtained prior to the second position.

16. A controller according to any one of claims 11 to 15, wherein the controller implements a control function which in turn provides a control output to adjusts the second position.

17. A controller according to claim 16, wherein the control function operates to force the measurement value toward a predetermined value.