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(54) INDUCTIVE COMPENSATION BASED CONTROL OF SYNCHRONOUS RECTIFICATION SWITCH

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H02M 7/217 (2006.01)
H02M 3/335 (2006.01)
H02M 7/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H02M 3/33507*** (2013.01); ***H02M 7/003*** (2013.01); ***H02M 7/217*** (2013.01); *H02M 3/33592* (2013.01)

(58) **Field of Classification Search**
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USPC 363/21.02, 21.03, 21.06, 21.14, 127, 363/146, 147
See application file for complete search history.

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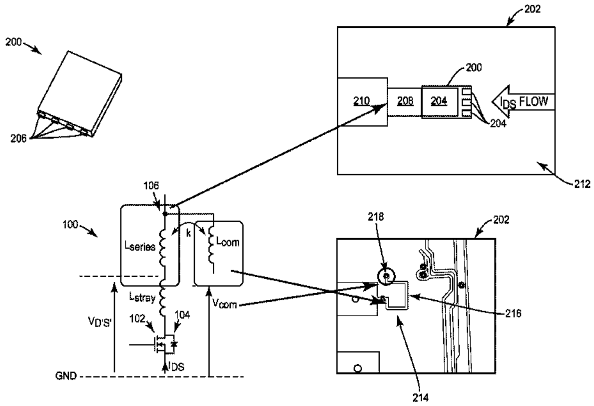
(57) ABSTRACT

An electronic device includes a synchronous rectification circuit having an actively controlled switching element through which resonant current flows during operation. The actively controlled switching element is disposed in a package which adds stray inductance to a main current path of the synchronous rectification circuit. The electronic device also includes a fixed inductor magnetically coupled to the stray inductance or an additional inductance in series with the stray inductance so that the fixed inductor is not in the main current path of the synchronous rectification circuit and change in current through the inductance to which the fixed inductor is magnetically coupled induces a reference voltage at the fixed inductor which is in phase with a zero crossing point of the resonant current at different switching frequencies of the actively controlled switching element. A corresponding method of controlling the electronic device is also described.

20 Claims, 14 Drawing Sheets



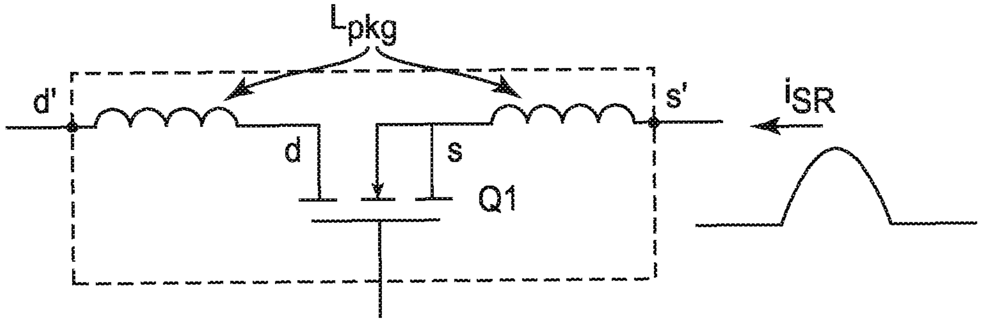


Figure 1

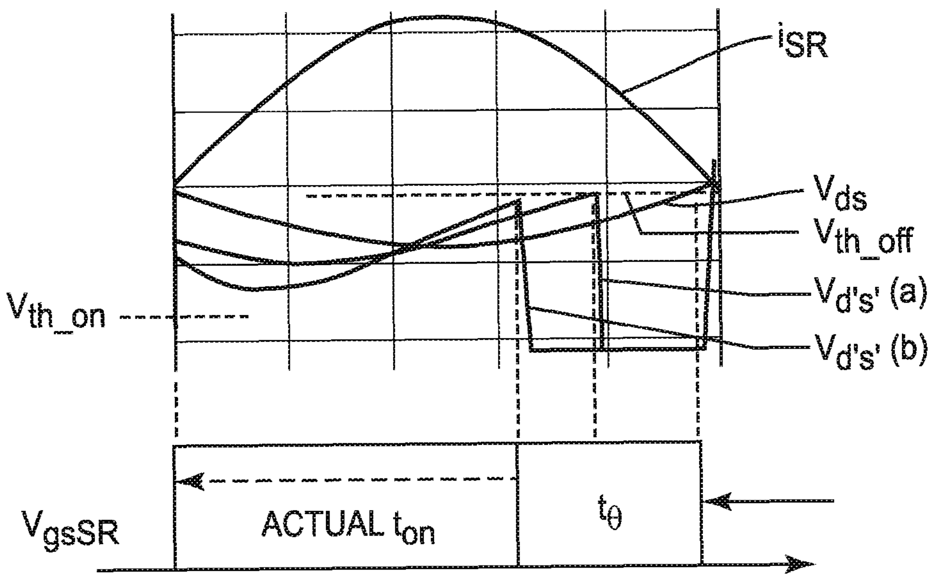


Figure 2

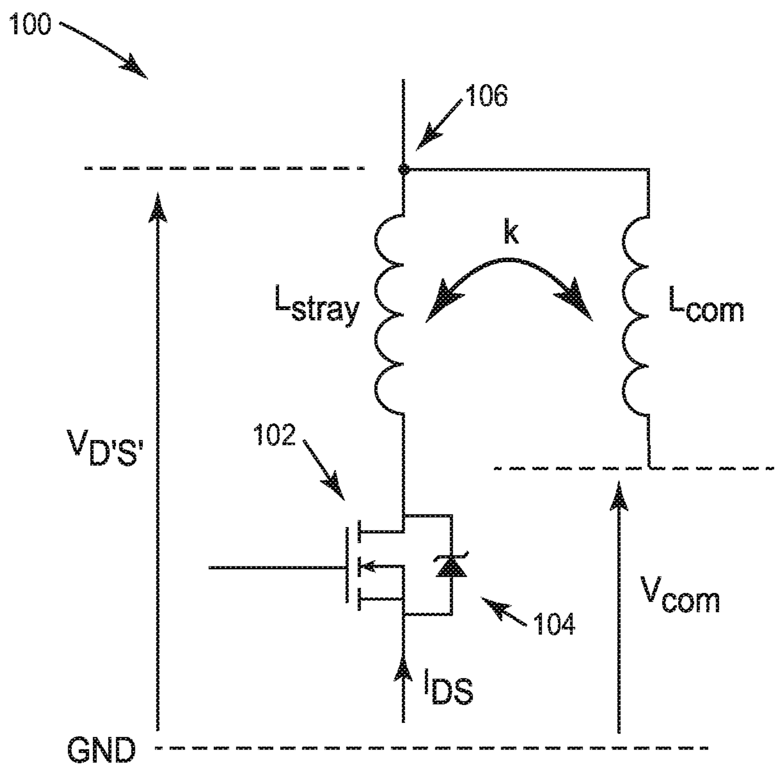


Figure 3

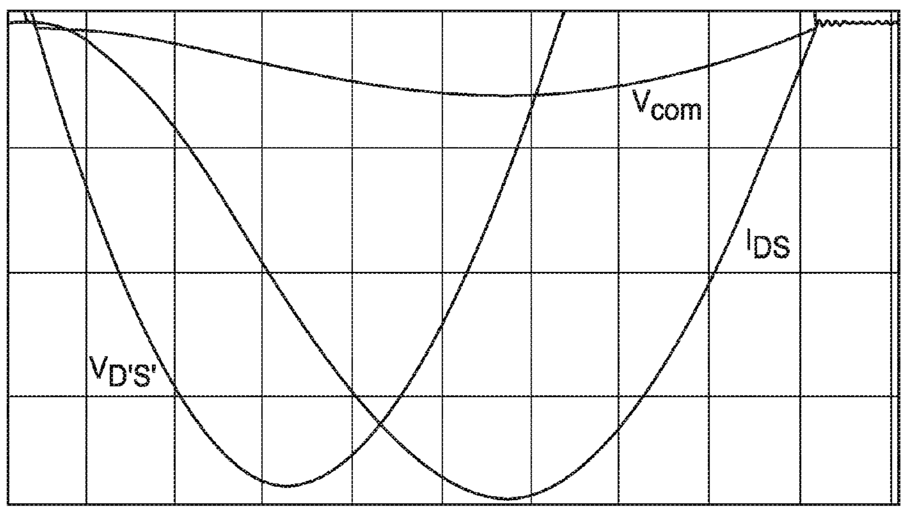


Figure 4

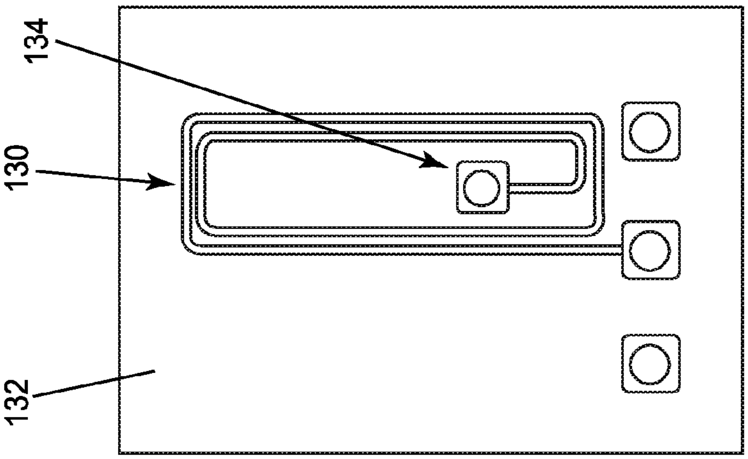


Figure 5B

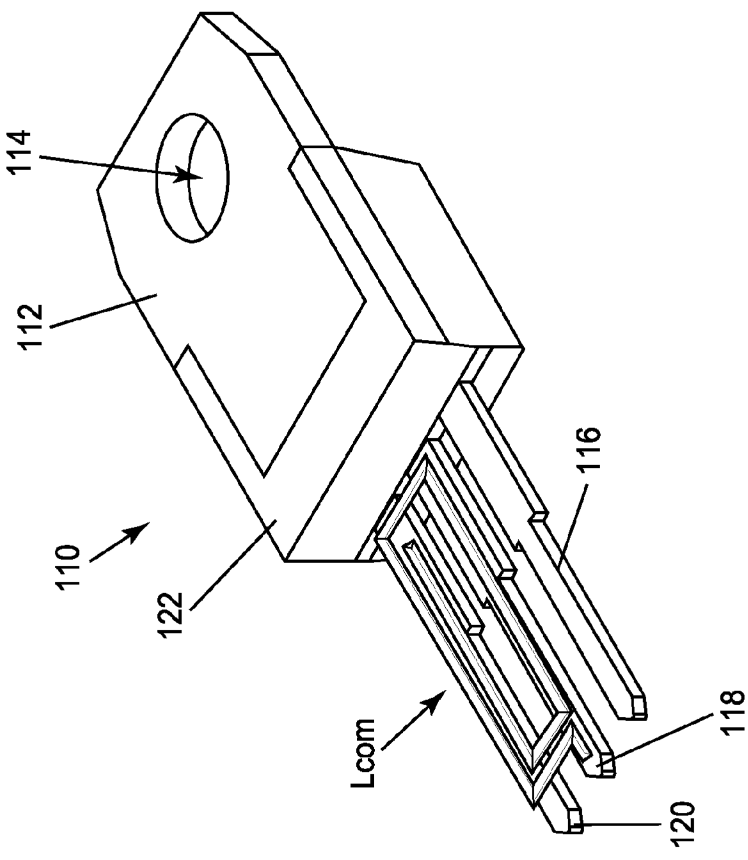


Figure 5A

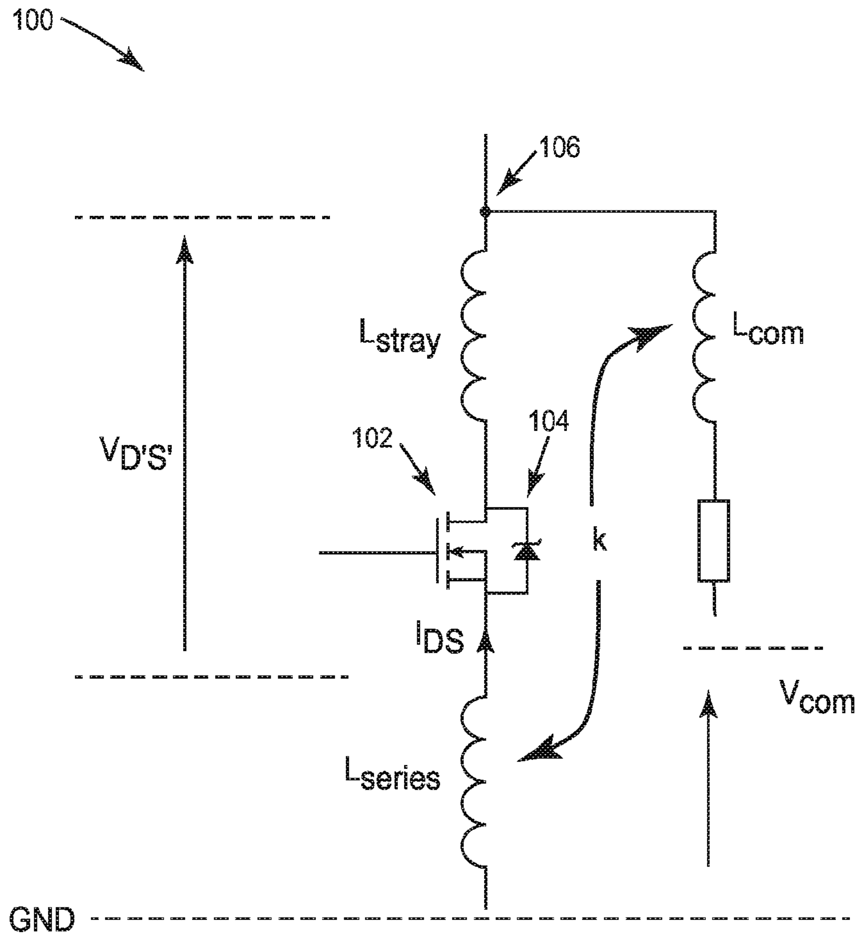


Figure 6

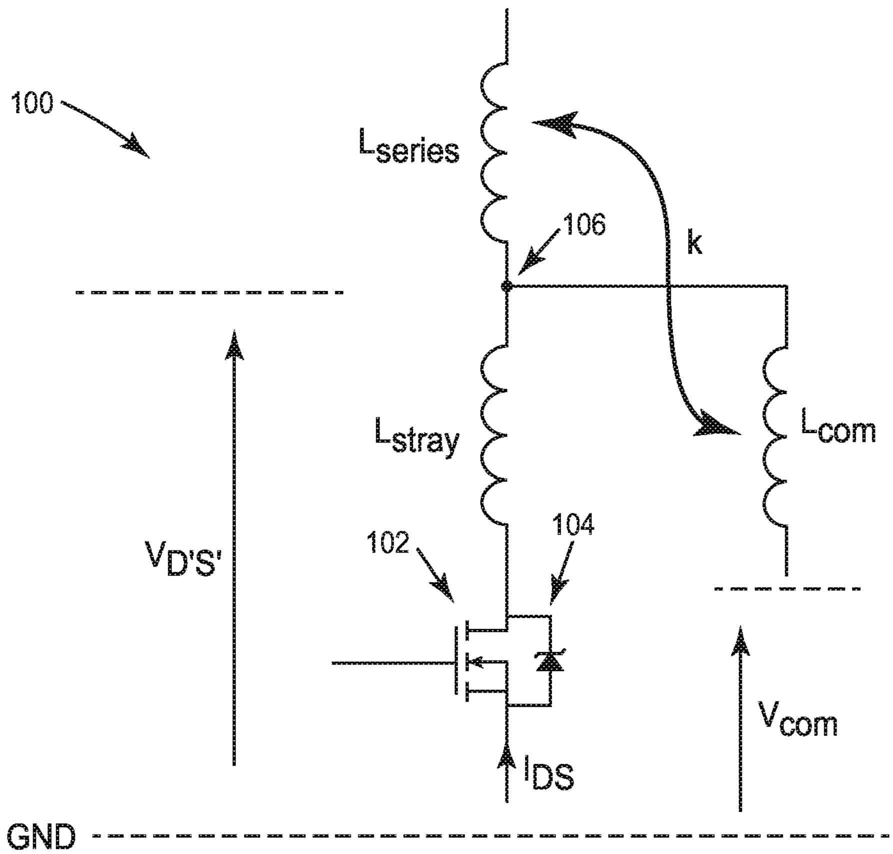


Figure 7

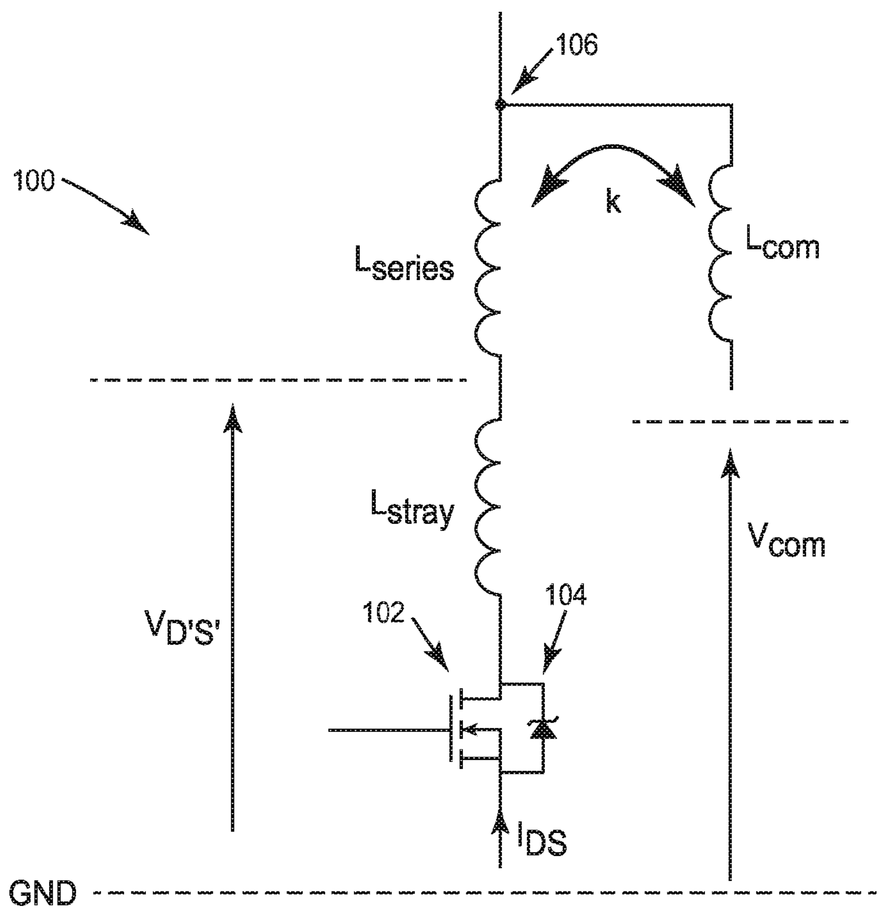
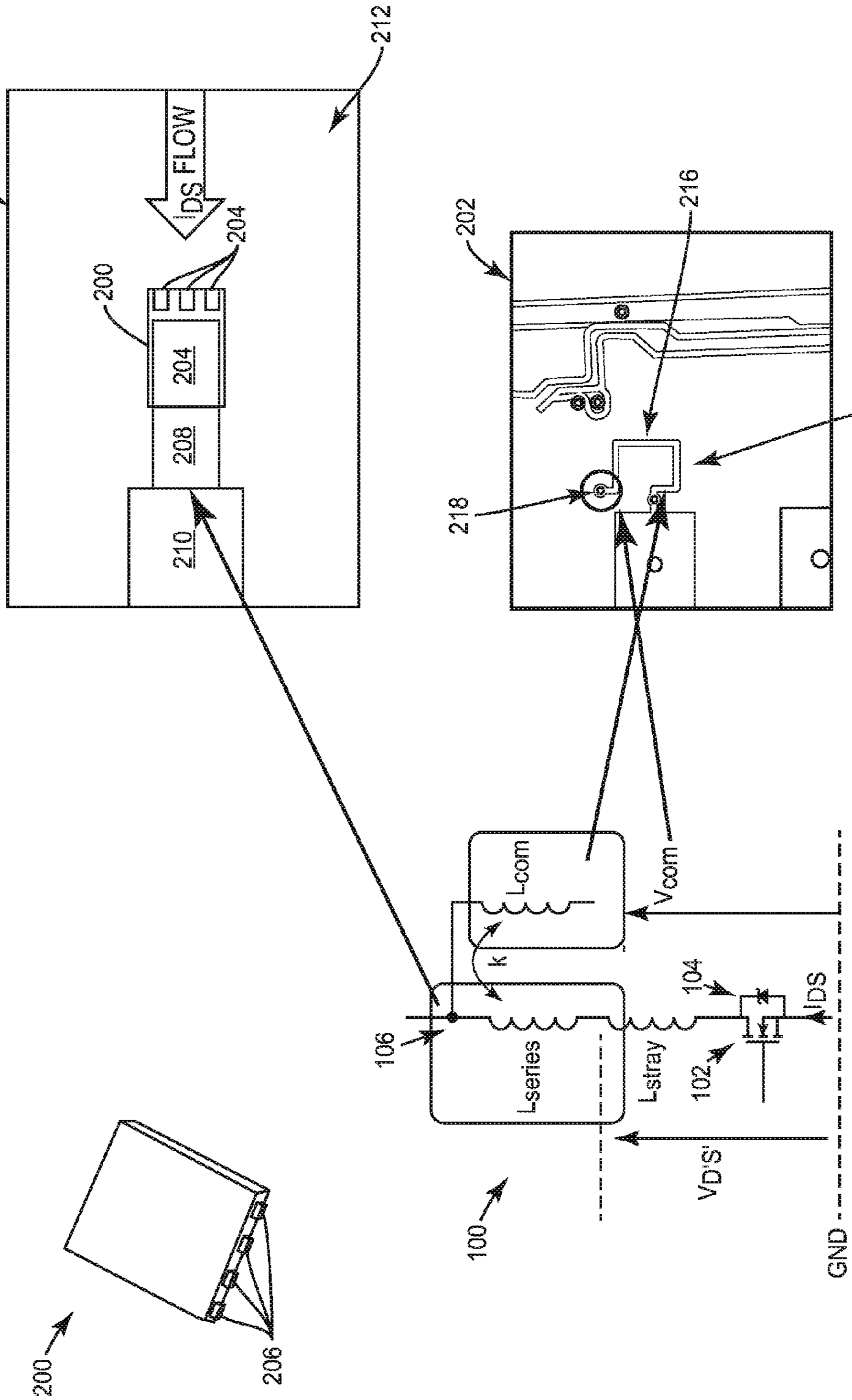
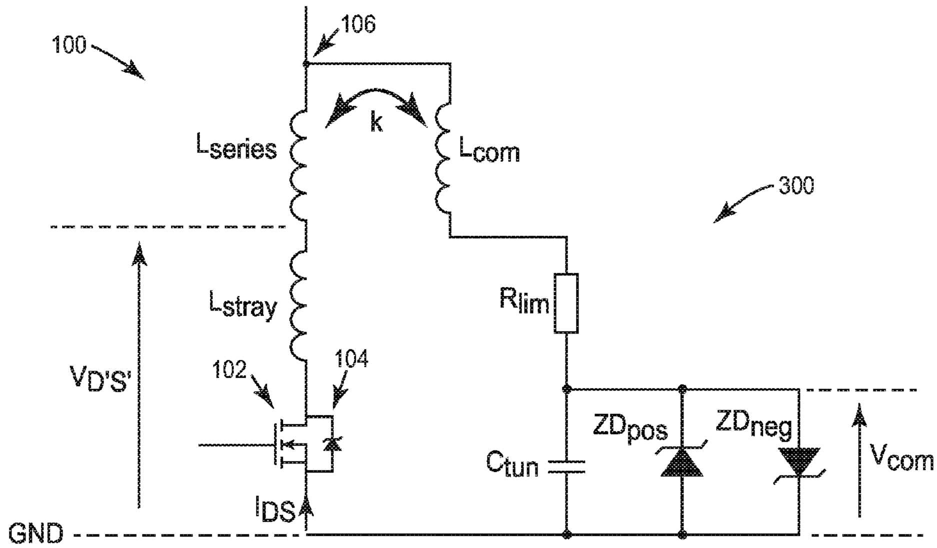


Figure 8



212
202
IDS FLOW
204
200
204
208
210
202
216
214
218
Lcom
k
Vcom
104
IDS
106
Lseries
Lstray
102
VD'S'
100
GND
200
206

Figure 9



106
100
k
L_{series}
L_{com}
300
L_{stray}
R_{lim}
$V_{D'S'}$
102
104
ZD_{pos}
ZD_{neg}
V_{com}
C_{tun}
I_{DS}
GND

Figure 10

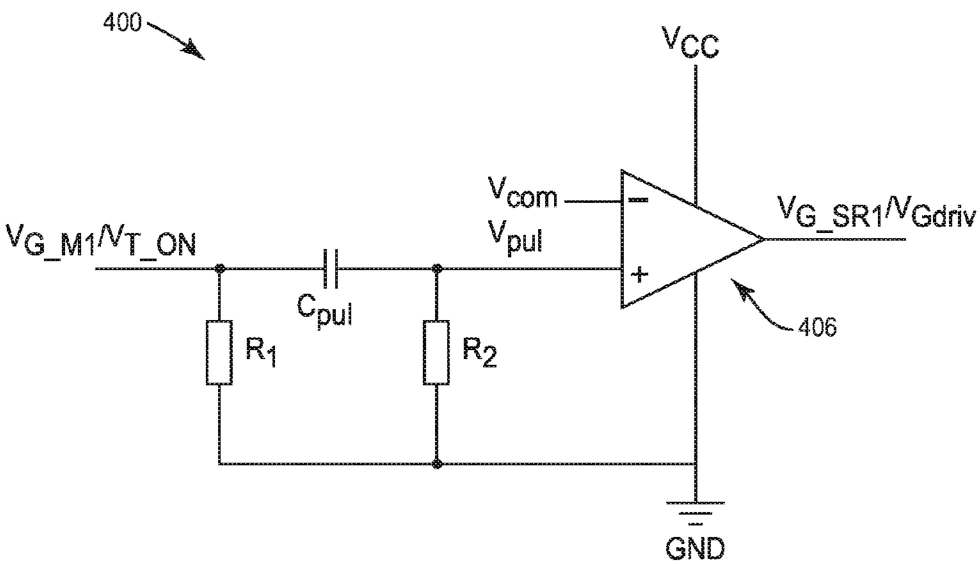


Figure 11

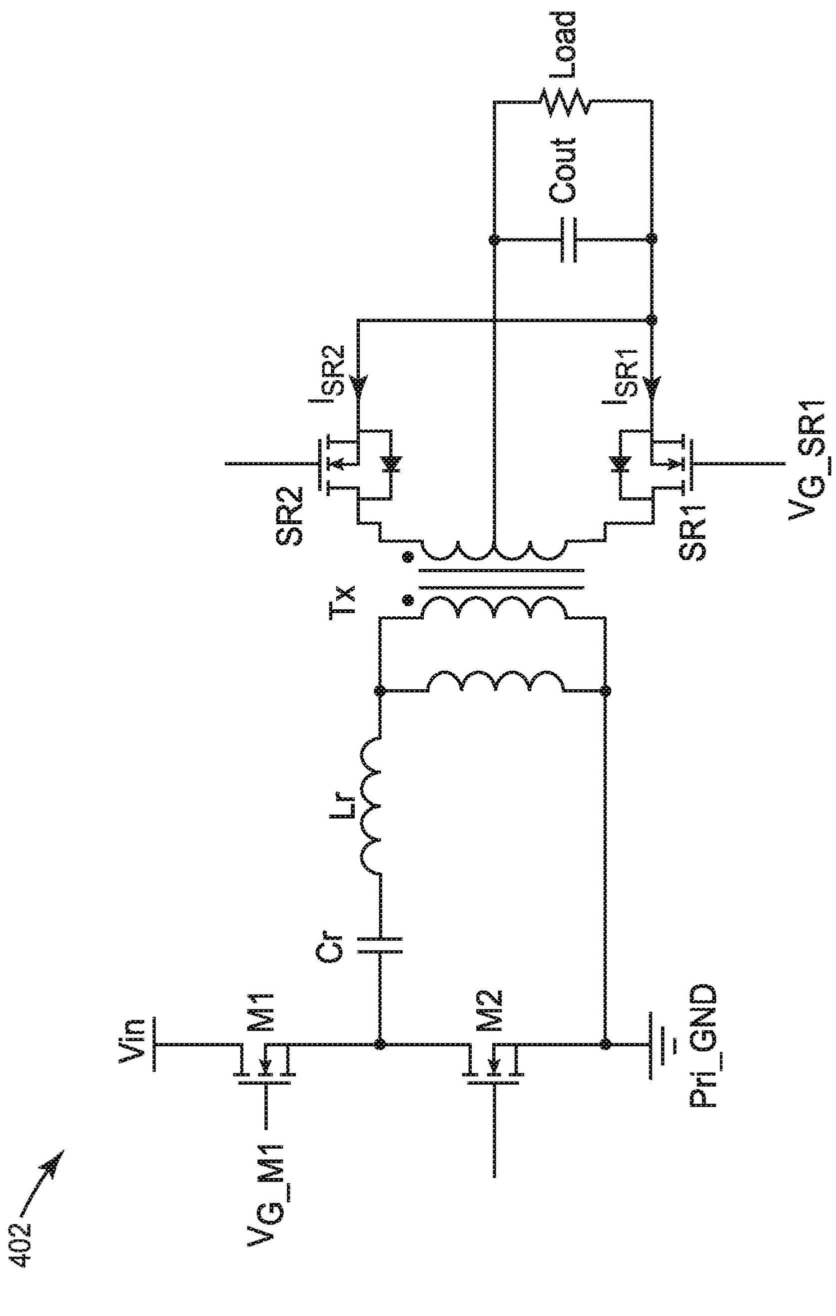

Load
Cout
I_SR2
I_SR1
SR2
SR1
V_G_SR1
Tx
Lr
Cr
Vin
M1
M2
Pri_GND
V_G_M1
402

Figure 12

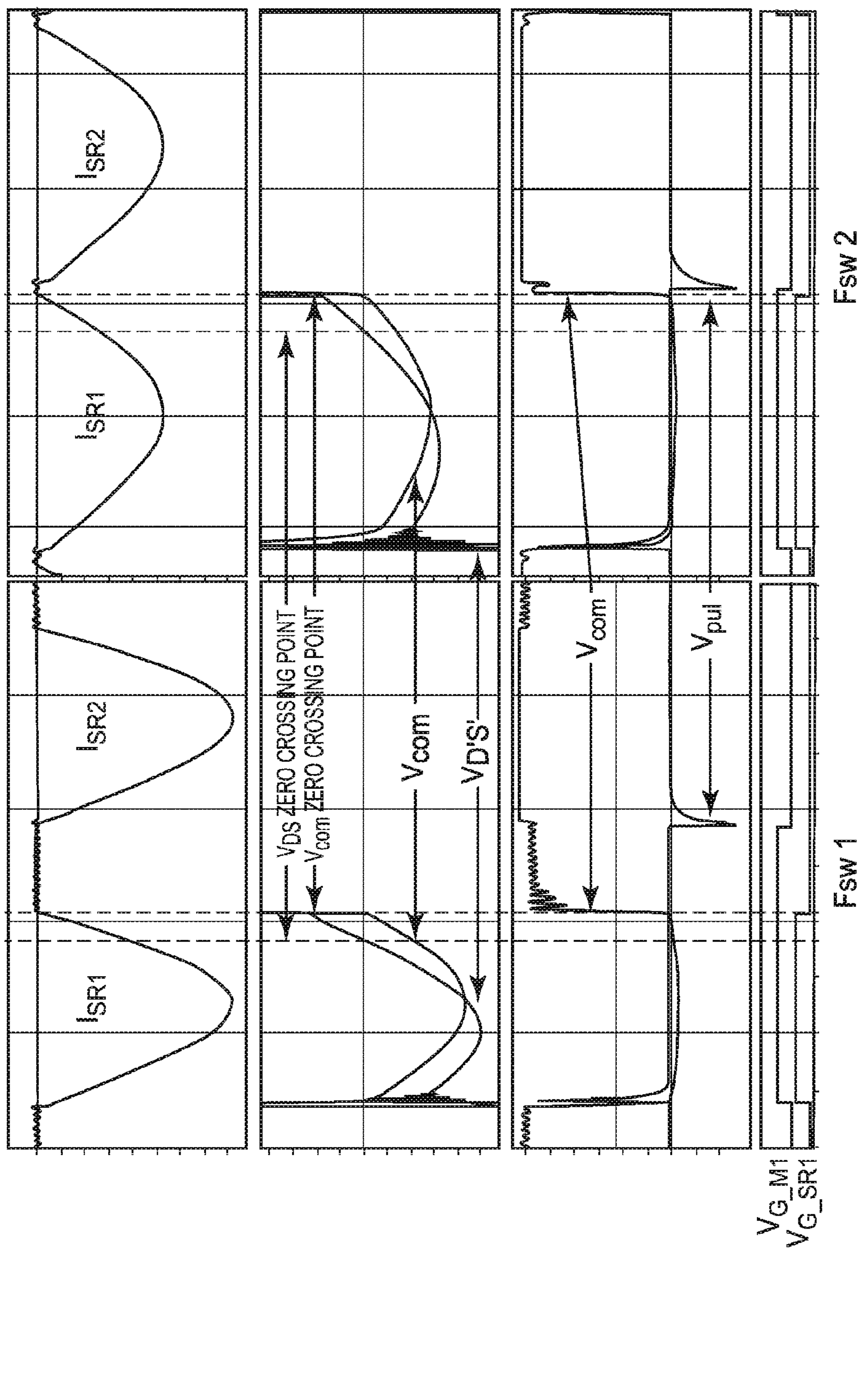
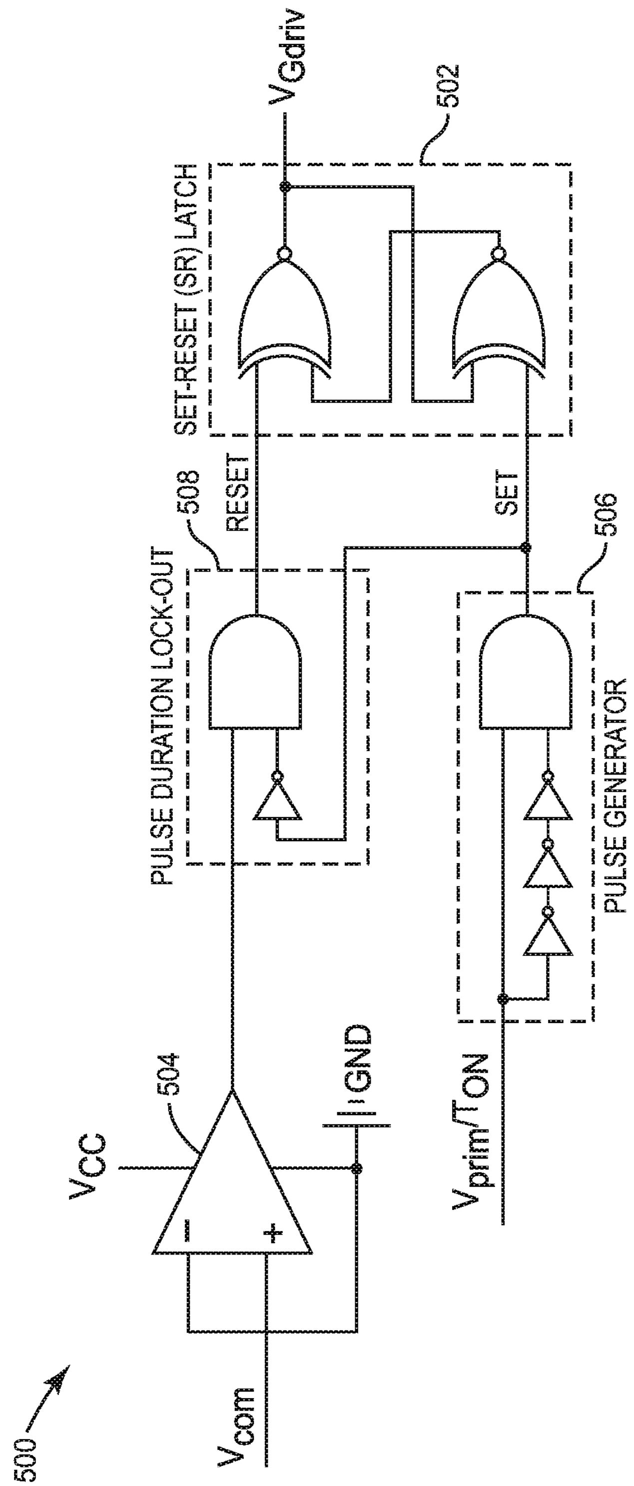

I_{SR1}
I_{SR2}
V_{DS} ZERO CROSSING POINT
V_{com} ZERO CROSSING POINT
V_{com}
$V_{D'S'}$
V_{pul}
Fsw 1
Fsw 2
V_{G_M1}
V_{G_SR1}

Figure 13



V_{Gdriv}
502
SET-RESET (SR) LATCH
508
RESET
SET
506
PULSE DURATION LOCK-OUT
PULSE GENERATOR
504
VCC
GND
V_{prim}/T_{ON}
V_{com}
500

Figure 14

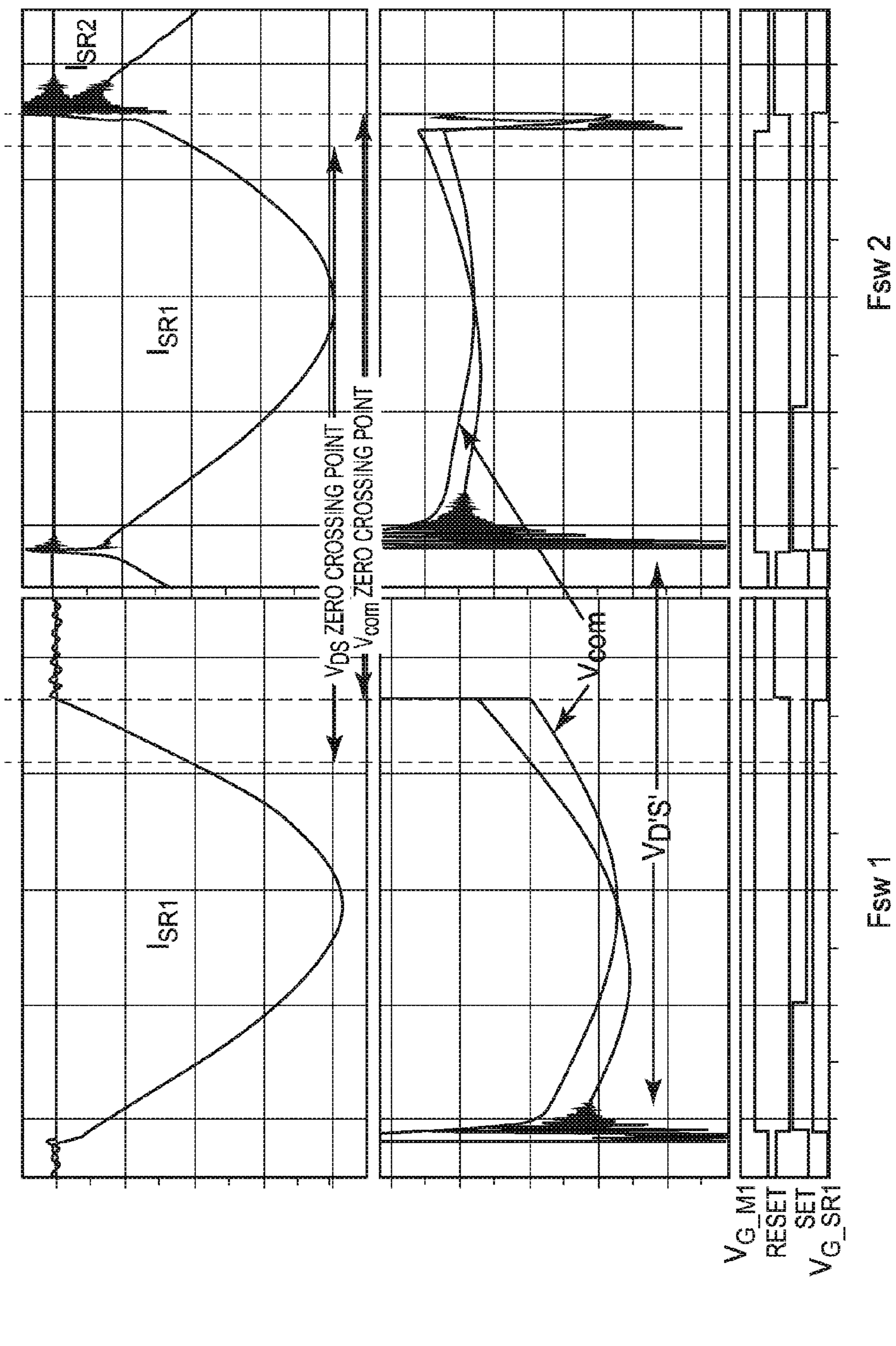

I_{SR2}
I_{SR1}
I_{SR1}
V_{DS} ZERO CROSSING POINT
V_{com} ZERO CROSSING POINT
V_{com}
$V_{D'S'}$
V_{G_M1}
RESET
SET
V_{G_SR1}
Fsw 1
Fsw 2

Figure 15

INDUCTIVE COMPENSATION BASED CONTROL OF SYNCHRONOUS RECTIFICATION SWITCH

TECHNICAL FIELD

The present application relates to synchronous rectification switches, in particular accurate control of synchronous rectification switches.

BACKGROUND

Accurate control of a synchronous rectification switch is difficult to achieve where zero crossing point detection of the resonant current through the switch is required. This includes accurate control of a synchronous rectification switch on the secondary side of an LLC converter, where accurate zero crossing point detection of the resonant current through the secondary side synchronous rectification switch directly affects efficiency.

FIG. **1** illustrates an exemplary synchronous rectification switch implemented as a MOSFET Q**1**. Due to the inductance (Lpkg) of the package in which the MOSFET Ts is included, the drain-source voltage $d_{d's'}$ measurable at the package terminals d', s' has a leading phase difference with respect to the current i_{SR} through the MOSFET Ts. The package is graphically illustrated as a dashed box in FIG. **1**. If the sensed $d_{d's'}$ voltage is used to detect the zero crossing point of the resonant current I_{SR}, the MOSFET Ts will be turned off while the device is still conducting current. This switching condition leads to poor efficiency.

FIG. **2** illustrates this problem in greater detail, where $V_{d's'}$ is the drain-source voltage measured at the package terminals d', s', i_{SR} is the resonant current through the MOSFET Ts, V_{ds} is the actual MOSFET drain-source voltage, V_{gsSR} is the control voltage applied to the gate of the MOSFET Ts, V_{th} corresponds to the threshold voltage of the MOSFET Ts, t_{on} is the actual time the MOSFET Ts is on, and t_θ represents the variability in the switch off period due to the phase difference between $d_{d's'}$ and I_{SR}. At a fixed frequency, the phase difference between $V_{d's'}$ and I_{SR} is fixed and therefore may be compensated easily. However, when the switching frequency changes, the phase difference also changes proportionally which further complicates the zero crossing point detection. This is illustrated in FIG. **2** by the two different $V_{d's'}$ curves (a) and (b), each one of which corresponds to a different switching frequency.

Several methods have been proposed to address accurate zero crossing point detection. These methods involve complex sensing circuitry or control algorithms. A simple and accurate solution is therefore desirable.

SUMMARY

According to an embodiment of an electronic device, the electronic device comprises a synchronous rectification circuit comprising an actively controlled switching element through which resonant current flows during operation. The actively controlled switching element is disposed in a package which adds stray inductance to a main current path of the synchronous rectification circuit. The electronic device also comprises a fixed inductor magnetically coupled to the stray inductance or an additional inductance in series with the stray inductance so that the fixed inductor is not in the main current path of the synchronous rectification circuit and change in current through the inductance to which the fixed inductor is magnetically coupled induces a reference voltage

at the fixed inductor which is in phase with a zero crossing point of the resonant current at different switching frequencies of the actively controlled switching element.

According to an embodiment of a method of controlling an electronic device which comprises a synchronous rectification circuit having an actively controlled switching element through which resonant current flows during operation, the actively controlled switching element being disposed in a package which adds stray inductance to a main current path of the synchronous rectification circuit, the method comprises: magnetically coupling a fixed inductor to the stray inductance or an additional inductance in series with the stray inductance so that the fixed inductor is not in the main current path of the synchronous rectification circuit and change in current through the inductance to which the fixed inductor is magnetically coupled induces a reference voltage at the fixed inductor which is in phase with a zero crossing point of the resonant current at different switching frequencies of the actively controlled switching element; and controlling switching of the actively controlled switching element based on a zero crossing point of the voltage induced at the fixed inductor.

Those skilled in the art will recognize additional features and advantages upon reading the following detailed description, and upon viewing the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

The elements of the drawings are not necessarily to scale relative to each other. Like reference numerals designate corresponding similar parts. The features of the various illustrated embodiments can be combined unless they exclude each other. Embodiments are depicted in the drawings and are detailed in the description which follows.

FIG. **1** illustrates a schematic diagram of a packaged synchronous rectification switch.

FIG. **2** illustrates voltage and current waveforms associated with the operation of the packaged synchronous rectification switch shown in FIG. **1**.

FIG. **3** illustrates a schematic diagram of an embodiment of a direct inductive compensation circuit for a synchronous rectification switch.

FIG. **4** illustrates voltage and current waveforms associated with the operation of the synchronous rectification switch shown in FIG. **3**.

FIG. **5**A illustrates a perspective view of an embodiment of a direct inductive compensation circuit for a packaged synchronous rectification switch.

FIG. **5**B illustrates a plan view of an embodiment of the direct inductive compensation circuit shown in FIG. **5**A.

FIG. **6** illustrates a schematic diagram of an embodiment of an indirect inductive compensation circuit for a synchronous rectification switch.

FIG. **7** illustrates a schematic diagram of another embodiment of an indirect inductive compensation circuit for a synchronous rectification switch.

FIG. **8** illustrates a schematic diagram of yet another embodiment of an indirect inductive compensation circuit for a synchronous rectification switch.

FIG. **9** illustrates different views of a circuit board based embodiment of an indirect inductive compensation circuit for a packaged synchronous rectification switch.

FIG. **10** illustrates a schematic diagram of an embodiment of phase tuning and protection circuitry for a synchronous rectification switch inductive compensation circuit.

FIG. **11** illustrates a schematic diagram of an embodiment of an analog controller for a synchronous rectification switch inductive compensation circuit.

FIG. **12** illustrates a schematic diagram of an embodiment of an LLC converter for which an inductive compensation circuit is used to accurately control the secondary side synchronous rectification switches of the LLC converter.

FIG. **13** illustrates voltage and current waveforms associated with the operation of the LLC converter shown in FIG. **12** and FIG. **11**.

FIG. **14** illustrates a schematic diagram of an embodiment of a digital controller for a synchronous rectification switch inductive compensation circuit.

FIG. **15** illustrates voltage and current waveforms associated with the operation of a synchronous rectification switch controlled by the digital controller shown in FIG. **14**.

DETAILED DESCRIPTION

According to the embodiments described herein, the zero crossing point of the resonant current through a synchronous rectification switch is detected by compensating the stray inductance of the switching circuit with a fixed inductor. The fixed inductor is magnetically coupled to the stray inductance or an additional inductance in series with the stray inductance, but is not in the main current path of the synchronous rectification circuit. This way, the sensed compensated voltage is in phase with the current through the device at different switching frequencies and the fixed inductor need not be sized to accommodate the full power of the switch. As a result, the control of the synchronous rectification switch instantly reacts to changes in switching frequency and is relatively temperature insensitive. In addition, active switches are not needed in the compensation network. Direct compensation and indirect compensation methods are described next in greater detail.

FIG. **3** illustrates an embodiment of the direct compensation method. In FIG. **3**, an electronic device includes a synchronous rectification circuit **100** comprising an actively controlled switching element **102** through which resonant current (I_{DS}) flows during operation. In an example, the synchronous rectification circuit **100** is an LLC converter and the actively controlled switching element **102** is the secondary side synchronous rectification switch of the LLC converter. In general, the actively controlled switching element **102** is disposed in a package which adds stray inductance (L_{stray}) to the main current path (I_{DS}) of the synchronous rectification circuit **100**. The dashed lines in FIG. **3** indicate external measurement points available at the package. Various package types can be used to house the actively controlled switching element **102**. The package is not shown in FIG. **3** for ease of illustration. The actively controlled switching element **102** is illustrated as a MOSFET (metal oxide semiconductor field effect transistor) having an integrated body diode **104**, but could be an IGBT (insulated gate bipolar transistor) or other type of actively controlled switching element.

In each case, a fixed inductor L_{com} is magnetically coupled to the stray inductance L_{stray} or an additional inductance in series with the stray inductance L_{stray} so that the fixed inductor L_{com} is not in the main current path I_{DS} of the synchronous rectification circuit **100**. According to an embodiment, the fixed inductor L_{com} is electrically connected at one terminal **106** to the inductance to which the fixed inductor L_{com} is magnetically coupled without being directly in series with the main power path I_{DS} of the actively controlled switching element **102**. In FIG. **3**, the fixed inductor L_{com} is shown magnetically coupled to the stray inductance L_{stray} of the package where k is the coupling factor. Change in current through the inductance to which the fixed inductor L_{com} is magnetically coupled induces a reference voltage V_{com} at the fixed inductor L_{com} which is in phase with the zero crossing point of the resonant current I_{DS} at different switching frequencies of the actively controlled switching element **102**.

FIG. **4** illustrates the voltage and current waveforms of primary interest. The fixed coupled inductor L_{com} compensates for the voltage drop along the stray inductance L_{stray}, thus the phase shifted $V_{D'S'}$ measurement at the terminals of the package is replaced by the compensated V_{com} measurement, which is always in phase with the resonant (commutation) current I_{DS} through the actively controlled switching element **102** at a wide range of switching frequencies.

With the direct compensation method, the fixed inductor L_{com} is magnetically coupled to the stray inductance L_{stray} of the package. Accordingly, the fixed inductor L_{com} and the coupling factor k should be tuned to the specific device package and L_{stray} values. The fixed inductor L_{com} can be designed into the device package itself, or can be an external inductor outside the device package. In an example, the fixed inductor L_{com} can be implemented as a copper track type inductor on a PCB (printed circuit board). The value of the coupling factor k varies depending on the design of the fixed inductor L_{com} and its proximity to the stray inductance L_{stray}, and the permeability of the material interposed between L_{com} and L_{stray}. However, since these parameters can be fixed, the value of k should also be a constant value with the direct compensation method. The measured voltage V_{com} is only a sensing point, therefore the fixed inductor L_{com} is not required to conduct any real current and therefore can be physically small. This way, the fixed inductor L_{com} and the stray inductance L_{stray} can be mismatched since the stray inductance L_{stray} is in the main current path I_{DS} of the synchronous rectification circuit **100** while the fixed inductor L_{com} is not in the main current path I_{DS}.

FIGS. **5**A and **5**B illustrate an exemplary package implementation of the direct compensation method. According to this embodiment, the actively controlled switching element **102** is a packaged in a TO (transistor outline) type package **110** such as the TO-220 package. The TO-220 package is a power package intended for power semiconductors and an example of a through-hole design rather than a surface-mount technology type of package. The top of the package **110** has a metal tab **112** with a hole **114** used in mounting the package **110** to a heat sink (not shown). The TO-220 package **110** has three leads **116**, **118**, **120** which protrude from a material **122** such as a mold compound which encases the actively controlled switching element **102**. The terminals include a gate lead **116**, a drain (collector) lead **118** and a source (emitter) lead **120**. The terminals **116**, **118**, **120** are a component of the overall stray inductance L_{stray} of the package **110**. Similar packages with two, four, five or seven leads are also available.

The fixed inductor L_{com} is disposed outside the package **110** according to this embodiment, as schematically illustrated in FIG. **5**A. In this example, the fixed inductor L_{com} is magnetically coupled to the stray inductance L_{stray} of the drain and source leads **118**, **120**. FIG. **5**B shows an implementation embodiment for the fixed inductor L_{com}, in which the fixed inductor L_{com} comprises a winding **130** on a circuit board **132** such as a PCB. The circuit board **132** can be positioned in close proximity to the package **110** so that the winding **130** is magnetically coupled to the stray inductance L_{stray} of the source (emitter) and/or drain (collector) leads

118, 120. For example, the circuit board 132 can be glued or otherwise attached to the leads 116, 118, 120. One terminal 134 of the winding 130 can be electrically connected to the drain (collector) lead 118 without being directly in series with the main power path of the actively controlled switching element 102. The actively controlled switching element 102 can be packaged in a different type of through-hole package e.g. such as the TO-247, and the fixed inductor L_{com} can be attached to the exterior surface of the package 110, embedded in the packaging material 122 or even disposed inside the package 110 with external points of contact for the direct compensation method.

FIG. 6 illustrates an embodiment of the synchronous rectification circuit 100 according to the indirect compensation method. According to this embodiment, an additional (series) inductor (L_{series}) is connected in series with the actively controlled switching element 102 between the source (emitter) of the switching element 102 and ground (GND). The fixed inductor L_{com} is magnetically coupled to the series inductor L_{series} to provide the compensated voltage measurement V_{com}. The fixed inductor L_{com} is electrically connected at one terminal 106 to the stray inductance L_{stray} without being directly in series with the main power path (I_{DS}) of the actively controlled switching element 102. The fixed inductor L_{com} is magnetically isolated from the stray inductance L_{stray} of the package.

FIG. 7 illustrates another embodiment of the synchronous rectification circuit 100 according to the indirect compensation method. According to this embodiment, the series inductor L_{series} is connected in series with the stray inductance of the package on the drain side of the actively controlled switching element and one terminal of the fixed inductor L_{com} is electrically connected between the series inductor and the stray inductance without being directly in series with the main power path (I_{DS}) of the actively controlled switching element.

FIG. 8 illustrates yet another embodiment of the synchronous rectification circuit 100 according to the indirect compensation method. The embodiment shown in FIG. 8 is similar to the embodiment shown in FIG. 7. Different however, the series inductor L_{series} is disposed on top of the package and the fixed inductor L_{com} is disposed on top of the series inductor L_{series} as schematically illustrated in FIG. 8. Also, the one terminal 106 of the fixed inductor L_{com} is electrically connected to the opposite terminal of the series inductor L_{series} as shown in FIG. 7. The series inductor L_{series} remains directly in the main power path (I_{DS}) of the actively controlled switching element 102.

FIGS. 6 through 8 illustrate different configurations of the indirect compensation method. In each case, the fixed inductor L_{com} is electrically connected at the drain (collector) potential of the synchronous rectification circuit 100 to maintain the same inductive voltage to be compensated for as in the direct compensation method. With the indirect compensation method, the mechanical design of the fixed inductor L_{com} is less restrictive in terms of available space and in terms of coupling to the stray inductance L_{stray} of the device package. The values of the series inductor L_{series} should be as small as possible since the series inductor L_{series} adds to the overall series inductance of the device. Furthermore, the design of the series inductor L_{series} should ensure that the current carrying capability of L_{series} matches that of the actively controlled switching element 102. The configuration shown in FIG. 6 where the series inductor L_{series} is on the source side of the switch 102 might involve additional circuitry, since an additional contact may be available for sensing a potential difference from common ground (source).

FIG. 9 illustrates an exemplary package implementation of the indirect compensation method. According to this embodiment, the actively controlled switching element 102 is disposed in a package 200 such as a surface mount type package like the SuperSO8 or S2O8 which is attached to a circuit board 202 such as a PCB. The circuit board 202 has terminals/pads 204 to which corresponding terminals 206 of the package 200 are to be attached. The circuit board 202 also has an added first winding 208 which connects the output of the package 200 to an output metal trace 210 formed in a first layer 212 of the circuit board 202. The first winding 208 formed in the first layer 212 of the circuit board 202 corresponds to the series inductor L_{series} previously described herein, and is in series with the stray inductance L_{stray} of the package 200. A second winding 214 formed in a second layer 216 of the circuit board 202 is magnetically coupled to the first winding 208. In FIG. 9, the series inductor winding 208 and the package 200 are disposed at a first side of the circuit board 202 and the fixed inductor winding 214 is disposed at a second side of the circuit board 202 opposite the first side. Also, the series inductor winding 208 is implemented as a copper trace formed in a first layer 212 of the circuit board 202 and the fixed inductor winding 214 has one or more turns and is formed in a second layer 216 of the circuit board 202. Further according to this embodiment, the fixed inductor winding 214 is electrically connected at one terminal 106 to the series inductor winding 214 by a conductive via 218 which extends through the circuit board.

Described next are various embodiments of control, phase tuning and protection circuitry for use with the synchronous rectification circuit and fixed inductor previously described herein.

FIG. 10 illustrates an embodiment phase tuning and protection circuitry 300 for use with the synchronous rectification circuit 100 and fixed inductor L_{com}. For either the direct or indirect compensation methods, the design of the fixed inductor L_{com} (direct compensation method) or the fixed inductor L_{com} and the series L_{series} (indirect compensation method) should compensate the phase difference caused by the stray inductance L_{stray}. Also, the fixed inductor L_{com} (direct compensation method) or the fixed inductor L_{com} and the series L_{series} (indirect compensation method) should fit a specific device package such as SuperSO8, TO-220, TO-247, etc. However, even the same device with the same package, manufactured under the same batch can have individual variations in L_{stray}. This can affect the phase compensation accuracy, which can be increased by adding a low value series capacitor C_{tun} for tuning the phase difference after the design of L_{com} (direct compensation method) or L_{com} and L_{series} (indirect compensation method) have been fixed. As such, C_{tun} compensates for the stray inductance differing from an expected nominal value and tunes the zero crossing point.

A high value resistor R_{lim} can be added in series with the fixed inductor L_{com} for limiting the current flow through the L_{com} sensing path to ground. Furthermore, two anti-parallel Zener diodes ZD_{pos} and ZD_{neg} can be placed in parallel with C_{tun} for limiting the maximum positive/negative voltage that can be seen by C_{tun} and the rest of the sensing circuitry. Other diode types are also possible as long as their threshold voltages are not too low that they turn on during normal operation. Since C_{tun} can be a very low value, close to the combined output capacitance of the Zener diodes ZD_{pos},

ZD_{neg} and the input capacitance of the sensing circuitry, the added parallel capacitance from these devices can have an influence in choosing the value of C_{tun}.

Various types of control circuits can be used to control the switching signal applied to the gate of the actively controlled switching element **102**. In each case, the control circuitry is operable to control switching of the actively controlled switching element **102** based on the zero crossing point of the reference voltage V_{com}.

FIG. **11** illustrates an embodiment of a single comparator controller **400**. The associated LLC converter **402** is shown in FIG. **12**. The fixed inductor L_{com} is magnetically coupled to the stray inductance L_{stray} of actively controlled switching element SR**1** and SR**2** or an additional inductance in series with these stray inductances. Each actively controlled switching element SR**1** and SR**2** is electrically connected to one terminal of a secondary transformer winding of the LLC converter **402**, and provides synchronous rectification on the secondary side of the LLC converter **402**. Only the control of actively controlled switching element SR**1** is described next. The same control is applied to actively controlled switching element SR**2** in connection with transistor M**2**.

The single comparator controller **400** also includes a single high speed comparator **406** which compares the reference voltage V_{com} against signal Vpul. The Vpul signal is a modified version of the V_{G_M1} signal which is the primary side driving signal for transistor M**1**. Signal V_{G_M1} goes into an RCR network formed by resistor R**1**, capacitor Cpul and resistor R**2**. The RCR network turns the square signal into a pulse type signal which triggers the turn on of V_{G_SR1} with V_{G_M1}, but goes back to zero voltage as soon as C_{pul} is charged and then generates a negative pulse when V_{G_M1} switches off and discharges C_{pul} via R_1 and R_2.

FIG. **13** shows the operation of the single comparator controller **400** under two different switching frequencies Fsw**1** and Fsw**2**. The simulated waveforms show the compensated sensing signals V_{com} are always in phase with the zero crossing points of I_{SR1}, which trigger the signals V_{G_SR1} to switch off. Whereas the original V_{DS} is always leading I_{SR1} in the zero crossing points with various phase differences. Absent the inductive compensation techniques described herein, such phase differences would have led to early switch off situations. FIG. **13** also shows the voltage comparison between V_{com} and V_{pul}. Here, V_{G_SR1} is triggered on with positive V_{pul} signals from V_{G_M1}. Signal V_{pul} then drops back to zero voltage once capacitor C_{pul} is completely charged and V_{com} goes negative during the conduction period of actively controlled switching element SR**1** (as seen by the negative current of I_{SR1}). Once the zero crossing point is detected and V_{com} goes positive, V_{G_SR1} is switched off even when V_{G_M1} continue to be on. This control is inherently safe since even if V_{G_SR1} is longer than V_{G_M1} and a zero crossing event is not detected, once V_{G_M1} is switched off, the negative pulse forces V_{com} to be higher than V_{pul} and therefore forcing a turn off of V_{G_SR1} in all cases.

FIG. **14** illustrates an embodiment of a logic based controller **500**. The logic based controller is based on a NOR gated set-reset (SR) latch **502** which holds the output V_{Gdriv} to positive when the set signal is detected and only switches to zero or negative depending on the logic technology when a reset signal is detected. The reset signal for this circuit **502** is the output of a high speed comparator **504**, which compares the reference voltage V_{com} signal against the ground/MOSFET source point. The set point is triggered by the primary side gate signal V_{G_M1} and this signal goes through a pulse generator **506** which can generate a pulse of specific length. Generally, the length of the set point should be $\ll V_{G\_M1}$. Furthermore, the reset signal is also controlled by a lock out circuit **508** which holds the reset signal to its previous value while set is positive. This is to protect the reset signal from false triggering at the beginning from switching oscillations. The output V_{Gdriv} of the SR latch **502** is the control signal for the gate driver of the actively controlled switching element **102**.

FIG. **15** shows the operation of the logic based controller **500** under two different switching frequencies Fsw**1** and Fsw**2**. Here, V_{G_M1} triggers the set pulse which triggers V_{G_SR1} to turn on. Signal V_{G_SR1} remains on until zero crossing of reference voltage V_{com} signal is detected and the reset signal is triggered which turns off V_{G_SR1} and the whole process starts again when the set signal is triggered. Unlike the single comparator controller **400**, V_{G_SR1} can remain on even when V_{G_M1} turns off. This is shown in the Fsw**2** waveforms where the switching frequency is higher than the resonant frequency of the LLC converter **402** and I_{SR1} does not reach zero before V_{G_M1} turns off. At this point, I_{SR1} naturally conducts from the negative direction into the positive direction, forcing a zero current crossing event which triggers a reset signal.

Terms such as "first", "second", and the like, are used to describe various elements, regions, sections, etc. and are also not intended to be limiting. Like terms refer to like elements throughout the description.

As used herein, the terms "having", "containing", "including", "comprising" and the like are open ended terms that indicate the presence of stated elements or features, but do not preclude additional elements or features. The articles "a", "an" and "the" are intended to include the plural as well as the singular, unless the context clearly indicates otherwise.

It is to be understood that the features of the various embodiments described herein may be combined with each other, unless specifically noted otherwise.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a variety of alternate and/or equivalent implementations may be substituted for the specific embodiments shown and described without departing from the scope of the present invention. This application is intended to cover any adaptations or variations of the specific embodiments discussed herein. Therefore, it is intended that this invention be limited only by the claims and the equivalents thereof.

What is claimed is:

1. An electronic device, comprising:

a synchronous rectification circuit comprising an actively controlled switching element through which resonant current flows during operation, the actively controlled switching element being disposed in a package which adds stray inductance to a main current path of the synchronous rectification circuit; and

a fixed inductor magnetically coupled to the stray inductance or an additional inductance in series with the stray inductance so that the fixed inductor is not in the main current path of the synchronous rectification circuit and change in current through the inductance to which the fixed inductor is magnetically coupled induces a reference voltage at the fixed inductor which is in phase with a zero crossing point of the resonant current at different switching frequencies of the actively controlled switching element.

2. The electronic device of claim **1**, wherein the fixed inductor is electrically connected at one terminal to the inductance to which the fixed inductor is magnetically coupled without being directly in series with the main power path of the actively controlled switching element.

3. The electronic device of claim **1**, wherein the fixed inductor and the inductance to which the fixed inductor is magnetically coupled are mismatched.

4. The electronic device of claim **1**, wherein the fixed inductor is disposed outside the package.

5. The electronic device of claim **4**, wherein the fixed inductor comprises a winding on a circuit board, the circuit board being positioned in close proximity to the package so that the winding is magnetically coupled to the stray inductance or the additional inductance in series with the stray inductance.

6. The electronic device of claim **1**, wherein the fixed inductor is attached to an exterior surface of the package so that the fixed inductor is magnetically coupled to the stray inductance or the additional inductance in series with the stray inductance.

7. The electronic device of claim **1**, wherein terminals of the package protrude from a material which encases the actively controlled switching element, the terminals being a component of the stray inductance, and wherein the fixed inductor is positioned in close proximity to the terminals of the package so that the fixed inductor is magnetically coupled to the terminals.

8. The electronic device of claim **1**, wherein the additional inductance comprises a series inductor electrically disposed in the main current path of the synchronous rectification circuit, and wherein the fixed inductor is magnetically coupled to the series inductor.

9. The electronic device of claim **8**, wherein the fixed inductor is electrically connected at one terminal to the series inductor without being directly in series with the main power path of the actively controlled switching element.

10. The electronic device of claim **9**, wherein the series inductor is electrically connected to a drain-side of the actively controlled switching element.

11. The electronic device of claim **8**, wherein the series inductor comprises a first winding on a circuit board, and wherein the fixed inductor comprises a second winding on the circuit board which is magnetically coupled to the first winding.

12. The electronic device of claim **8**, wherein the series inductor and the package are disposed at a first side of a circuit board, and wherein the fixed inductor is disposed at a second side of the circuit board opposite the first side.

13. The electronic device of claim **12**, wherein the series inductor comprises a copper trace formed in a first layer of the circuit board, and wherein the fixed inductor comprises a winding formed in a second layer of the circuit board.

14. The electronic device of claim **12**, wherein the fixed inductor is electrically connected at one terminal to the series inductor by a conductive via which extends through the circuit board.

15. The electronic device of claim **8**, wherein the fixed inductor is disposed on top of the series inductor.

16. The electronic device of claim **1**, further comprising a control circuit operable to control switching of the actively controlled switching element based on the zero crossing point of the reference voltage.

17. The electronic device of claim **1**, further comprising circuitry operable to compensate for the stray inductance differing from an expected nominal value.

18. The electronic device of claim **1**, wherein the synchronous rectification circuit is an LLC converter and the actively controlled switching element is electrically connected to one terminal of a secondary transformer winding of the LLC converter.

19. The electronic device of claim **1**, further comprising:

a resistor and a capacitor connected in series between the fixed inductor and ground; and

a first diode and a second diode connected in parallel with the capacitor,

wherein the resistor is configured to limit the current through the resistor and the capacitor,

wherein the capacitor is configured to tune the zero crossing point,

wherein the first and the second diodes are configured to limit the voltage across the capacitor.

20. A method of controlling an electronic device which comprises a synchronous rectification circuit having an actively controlled switching element through which resonant current flows during operation, the actively controlled switching element being disposed in a package which adds stray inductance to a main current path of the synchronous rectification circuit, the method comprising:

magnetically coupling a fixed inductor to the stray inductance or an additional inductance in series with the stray inductance so that the fixed inductor is not in the main current path of the synchronous rectification circuit and change in current through the inductance to which the fixed inductor is magnetically coupled induces a reference voltage at the fixed inductor which is in phase with a zero crossing point of the resonant current at different switching frequencies of the actively controlled switching element; and

controlling switching of the actively controlled switching element based on a zero crossing point of the voltage induced at the fixed inductor.

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