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(54) **SYSTEM AND METHOD FOR IMPROVING CONVERTER EFFICIENCY**

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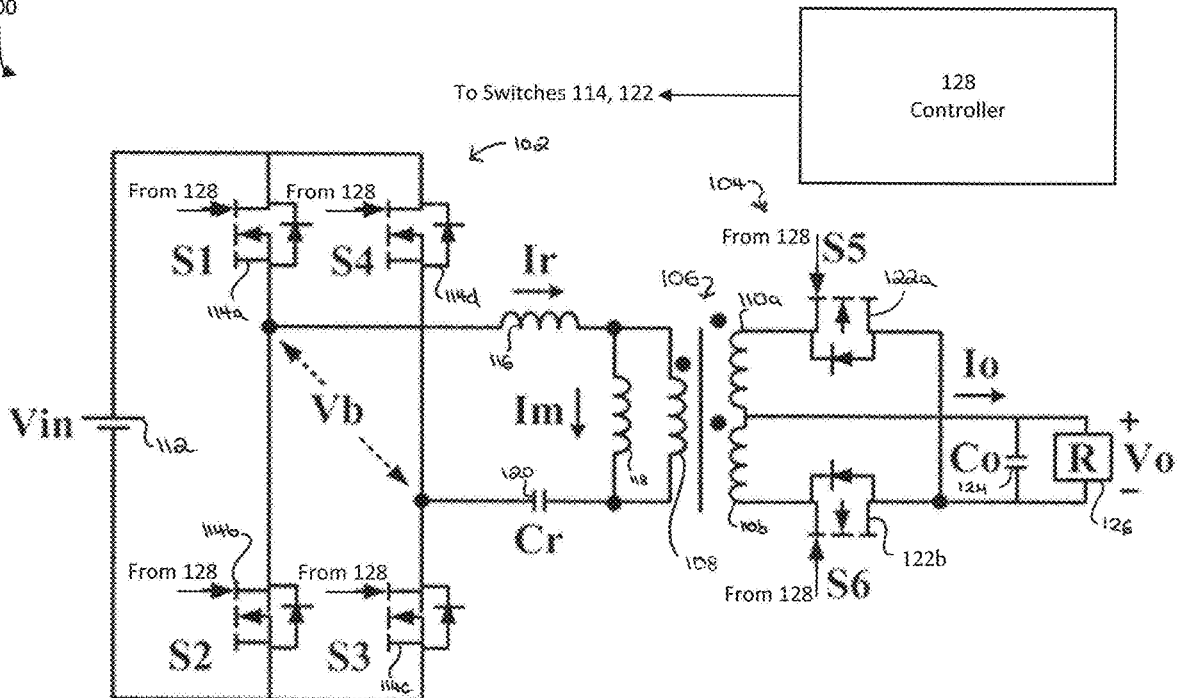
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(57) **ABSTRACT**

According to aspects of the disclose, a converter system includes a primary-side circuit configured to be coupled to an energy source, a secondary-side circuit configured to be coupled to a load, the secondary-side circuit including an energy storage device and at least one switching device configured to control a load current provided by the energy storage device to the load, and a controller configured to be coupled to the primary-side circuit and the secondary-side circuit, the controller being further configured to determine a parameter indicative of an energy level of the energy storage device, and control, based on the parameter indicating that the energy level of the energy storage device is below a discharge energy level, the at least one switching device to be in an open and non-conducting position.
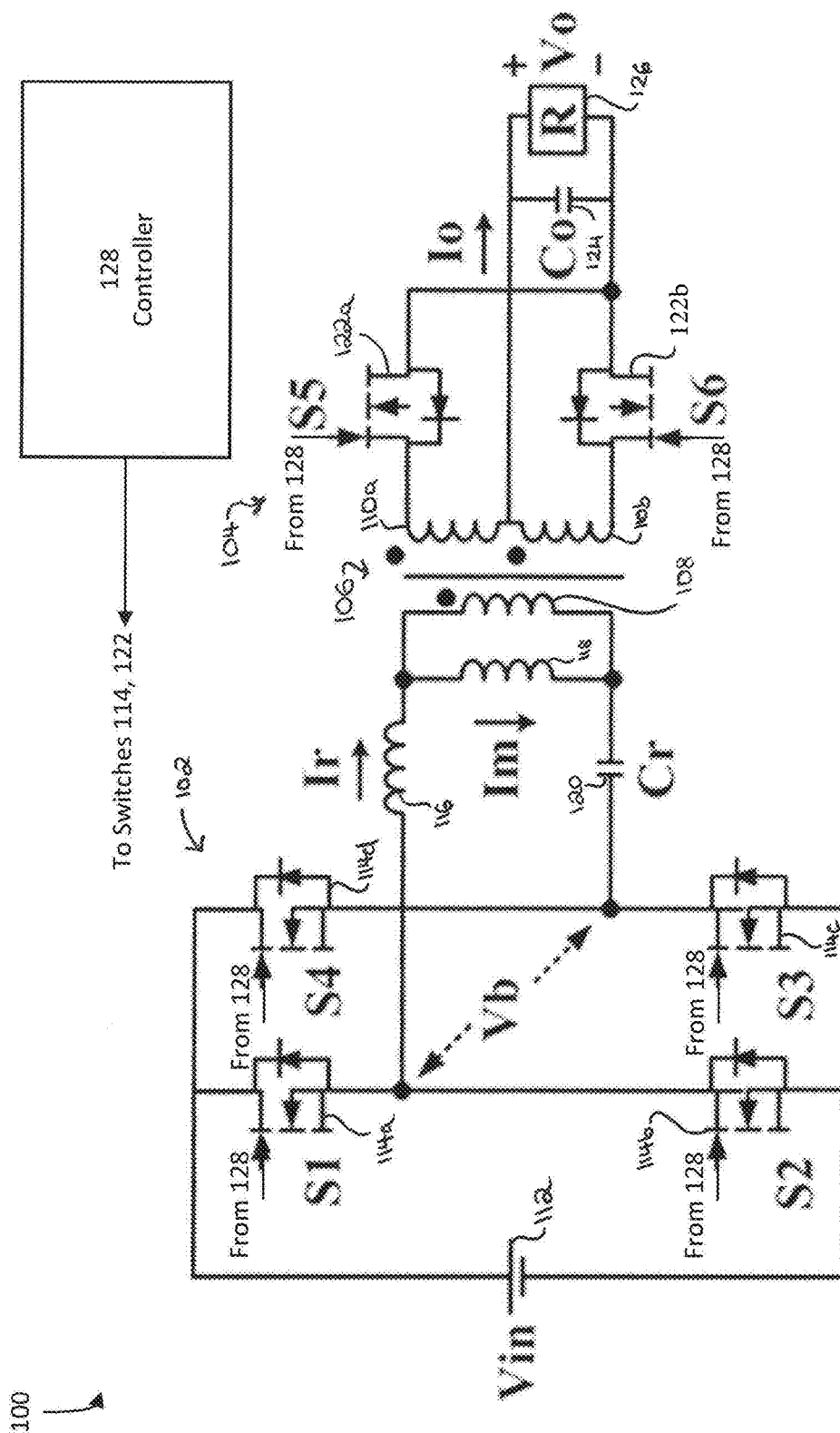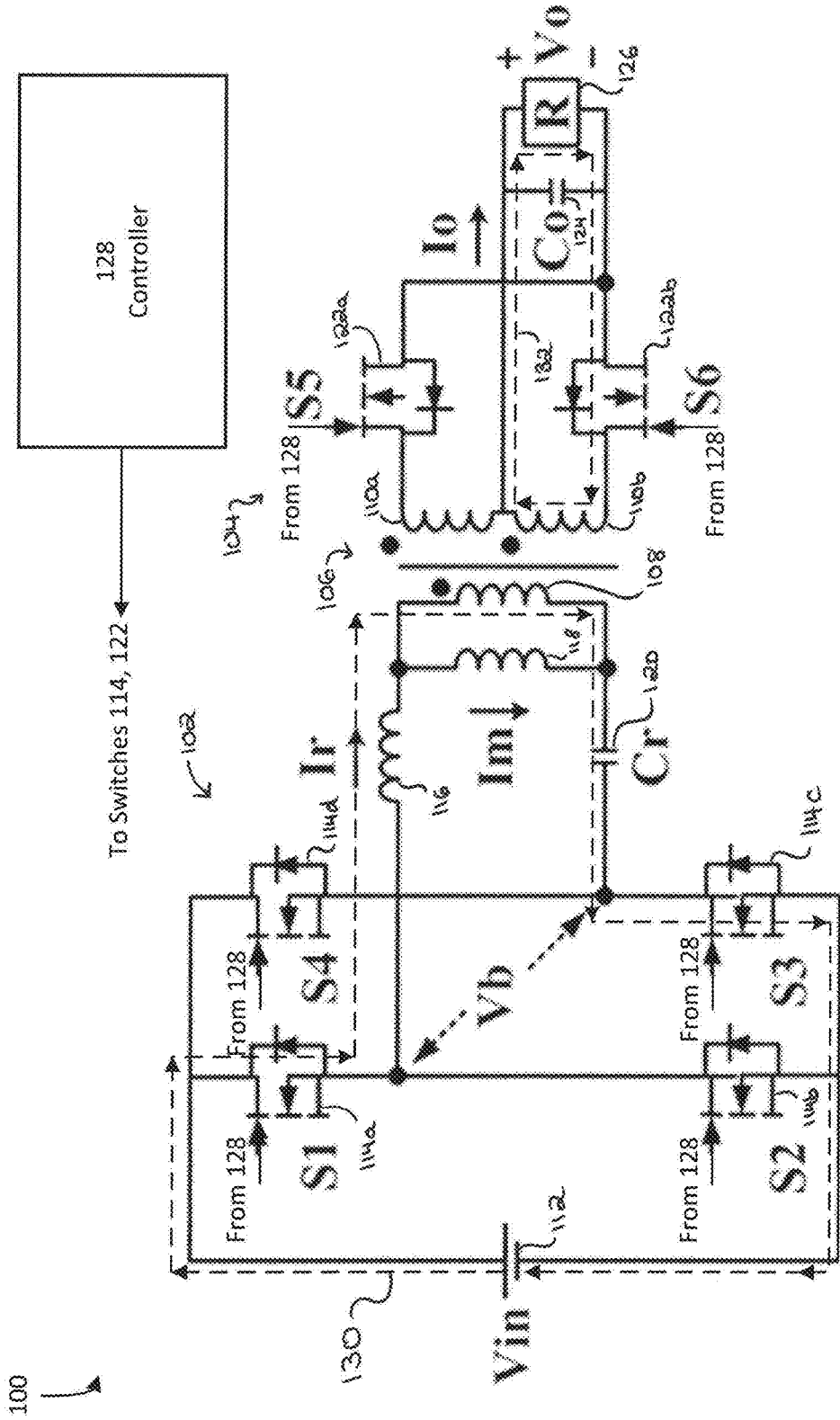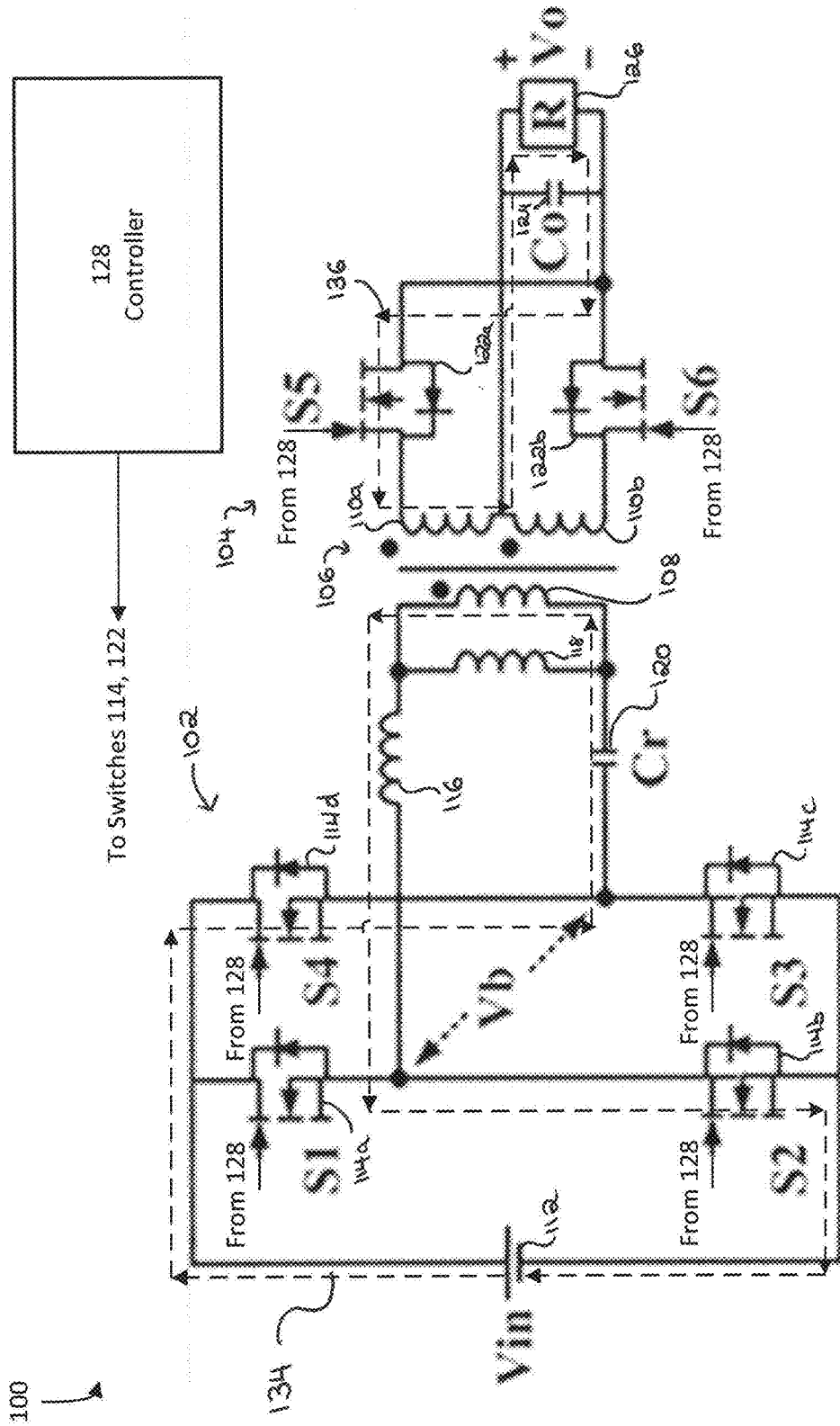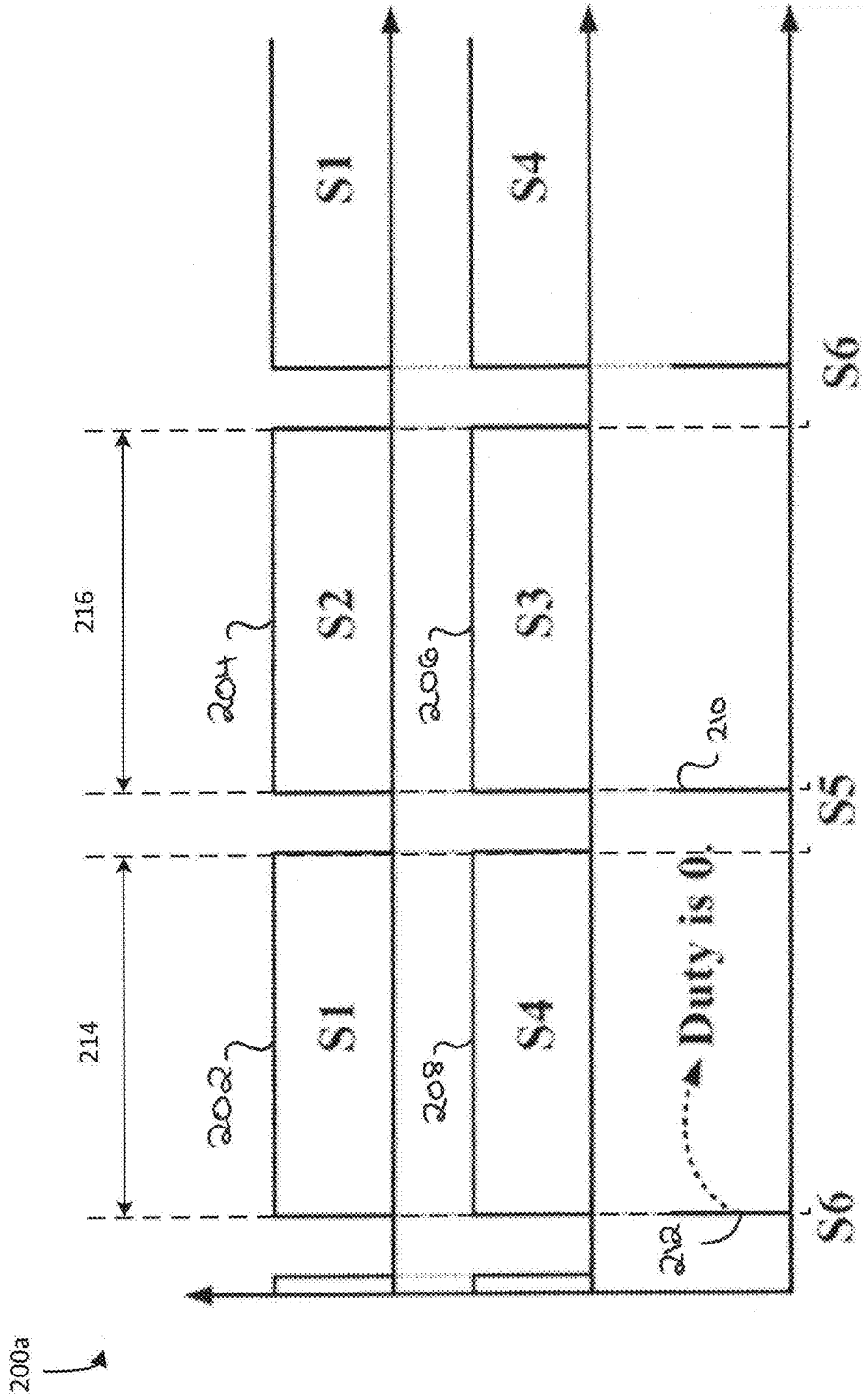
FIG. 1A

FIG. 1B

FIG. 1C

FIG. 2A

FIG. 2B

FIG. 2C

FIG. 3

FIG. 4

FIG. 5

600

504

502

602

A

B

B

A

Load

Section 1   Section 2   Section 3

604   606   608

FIG. 6

700

702
Begin

704
Determine Phase
Angle

706
Determine Graph
Section

708
Determine
Selected Duty
Cycle

710
Provide PWM
Signal

712
End
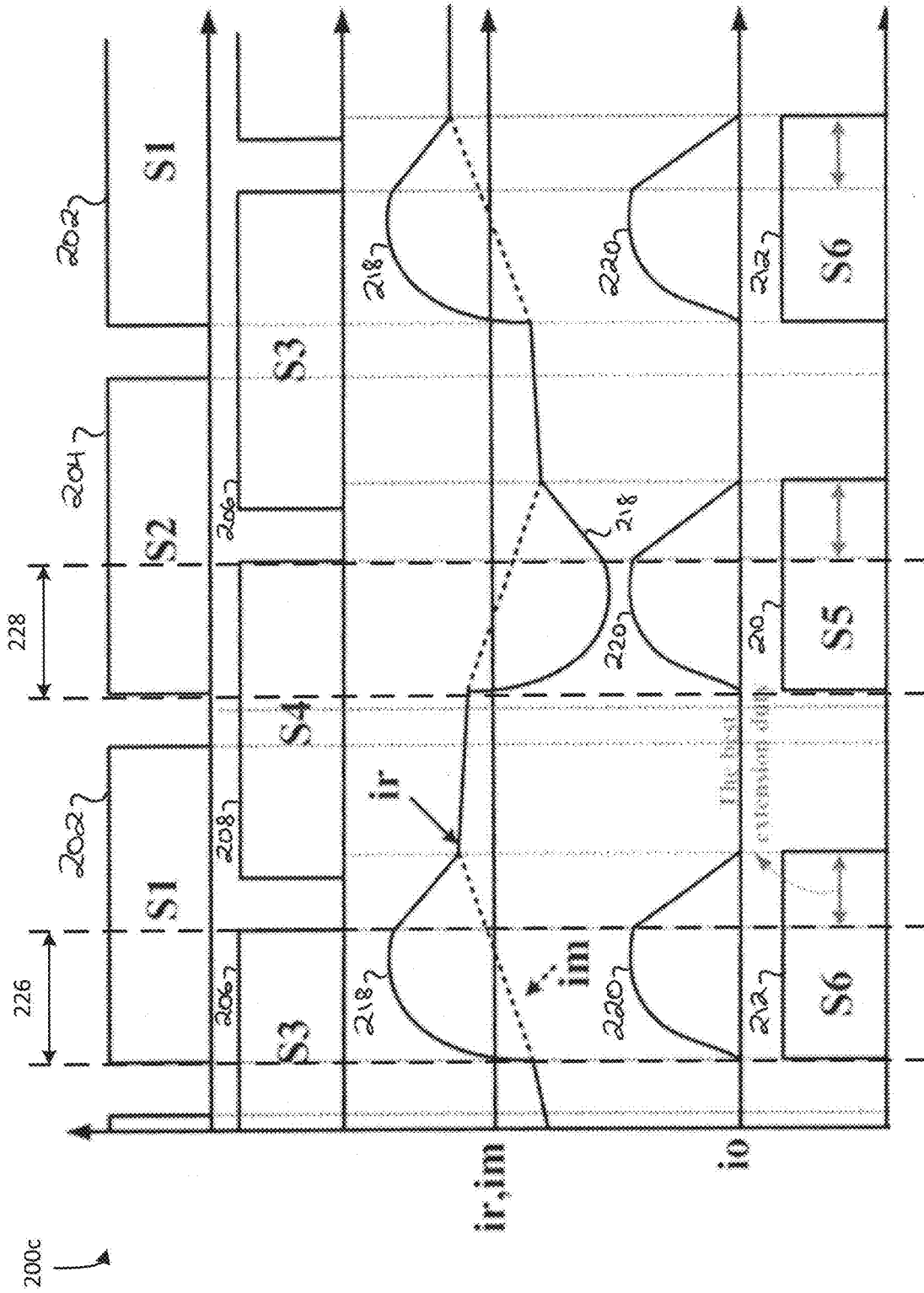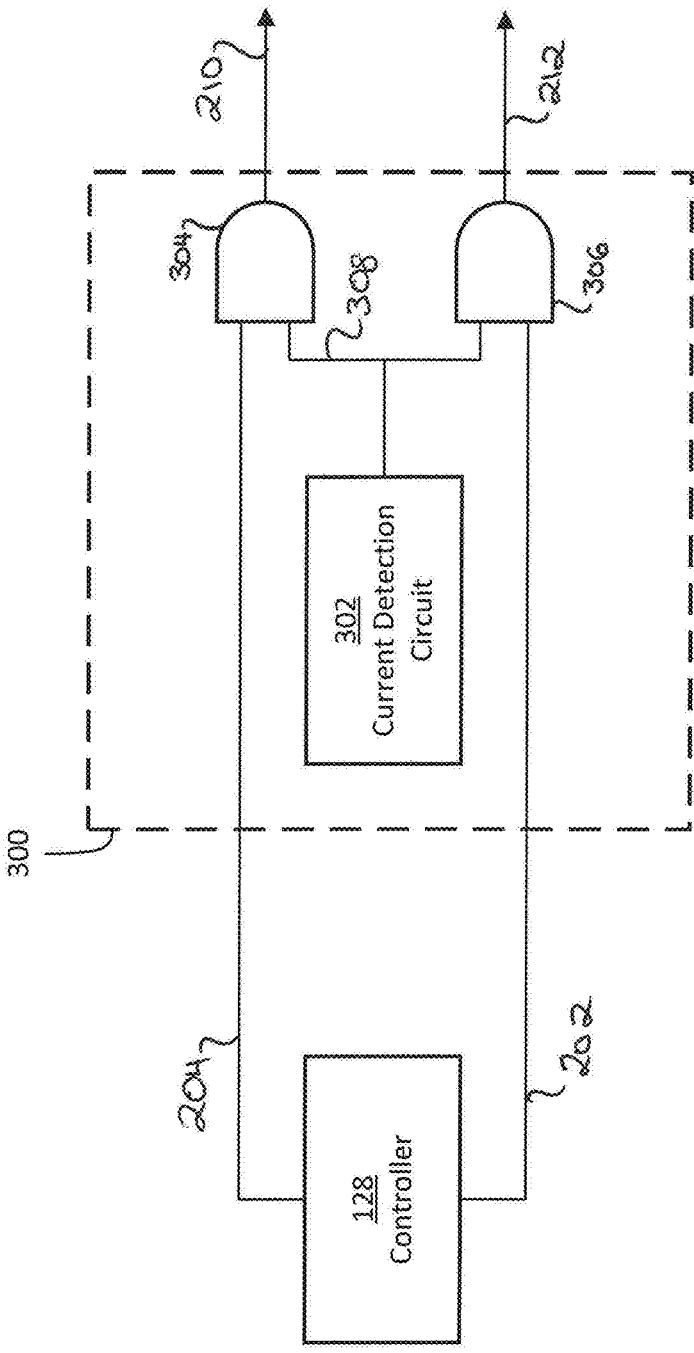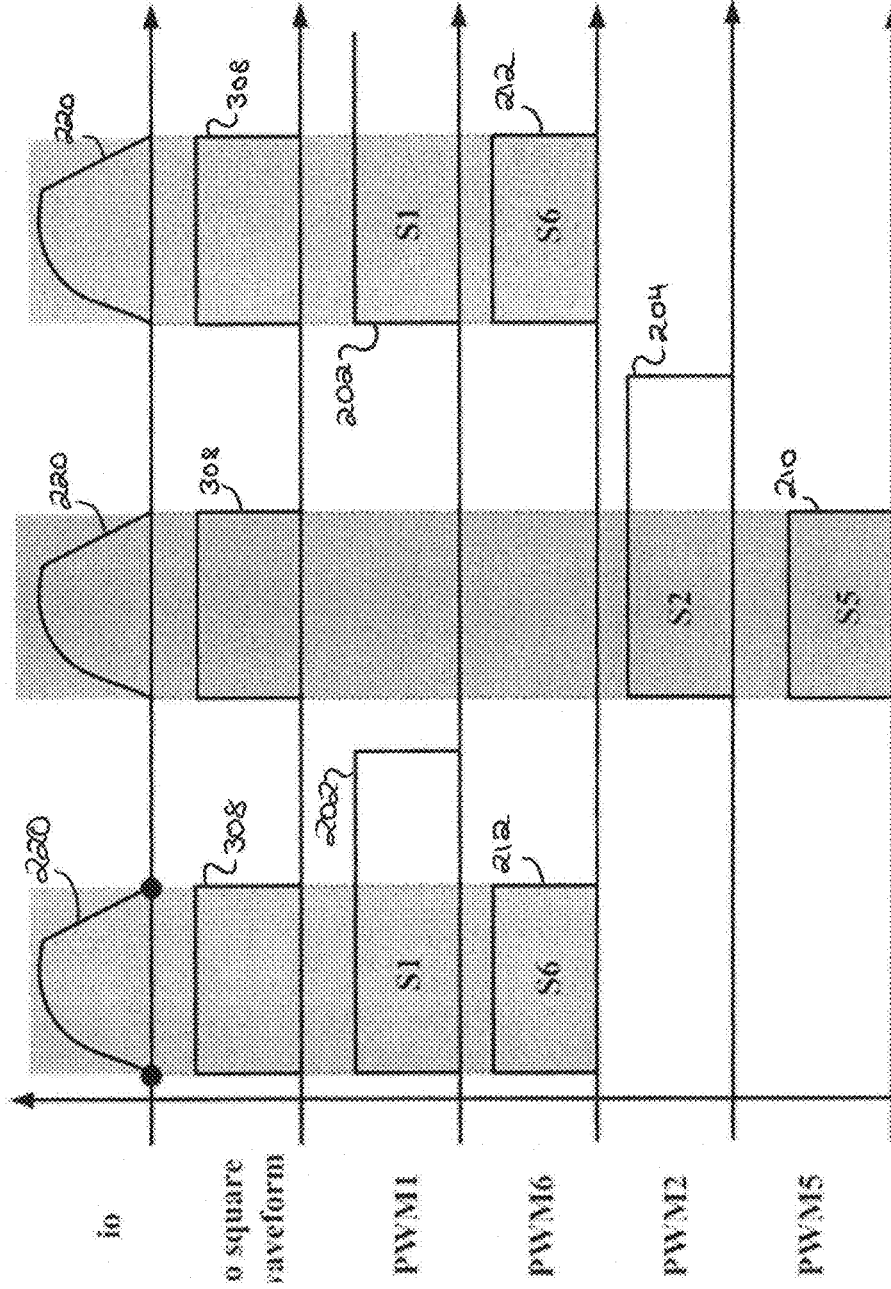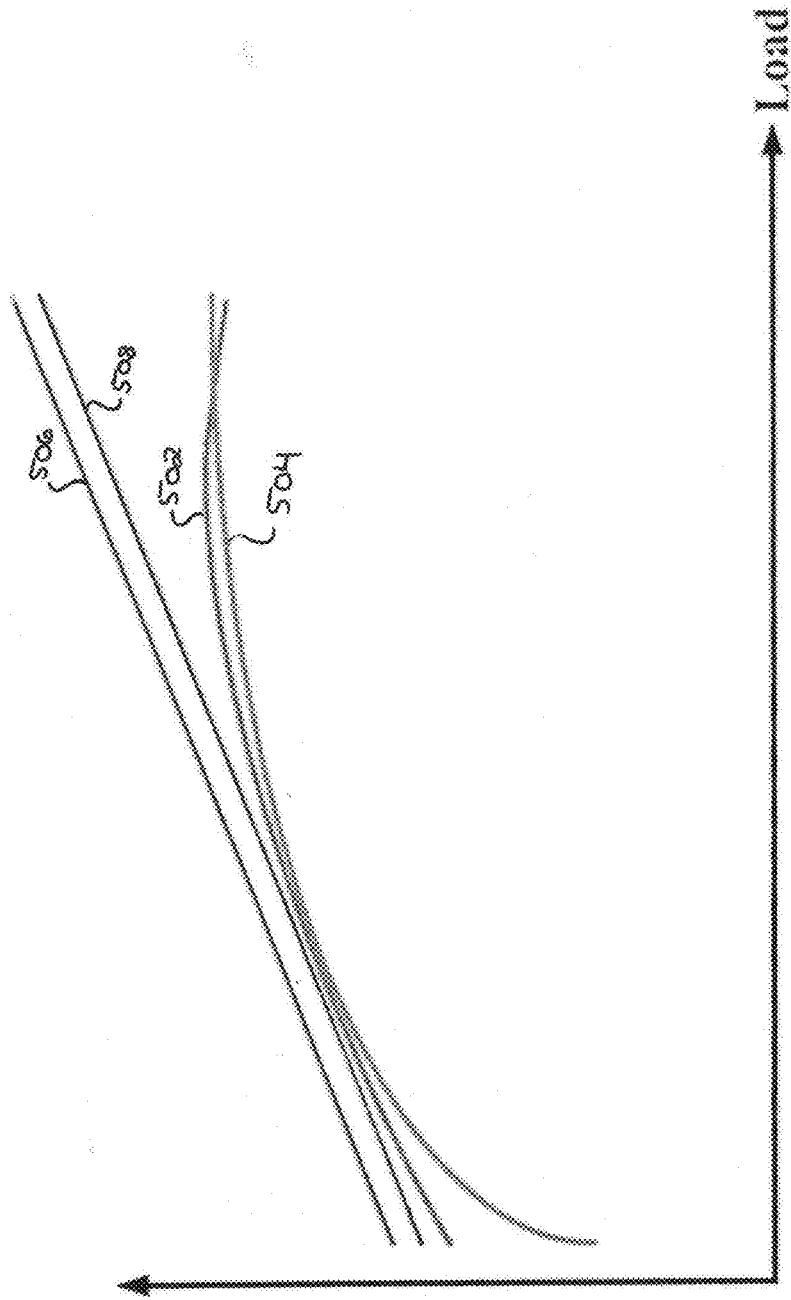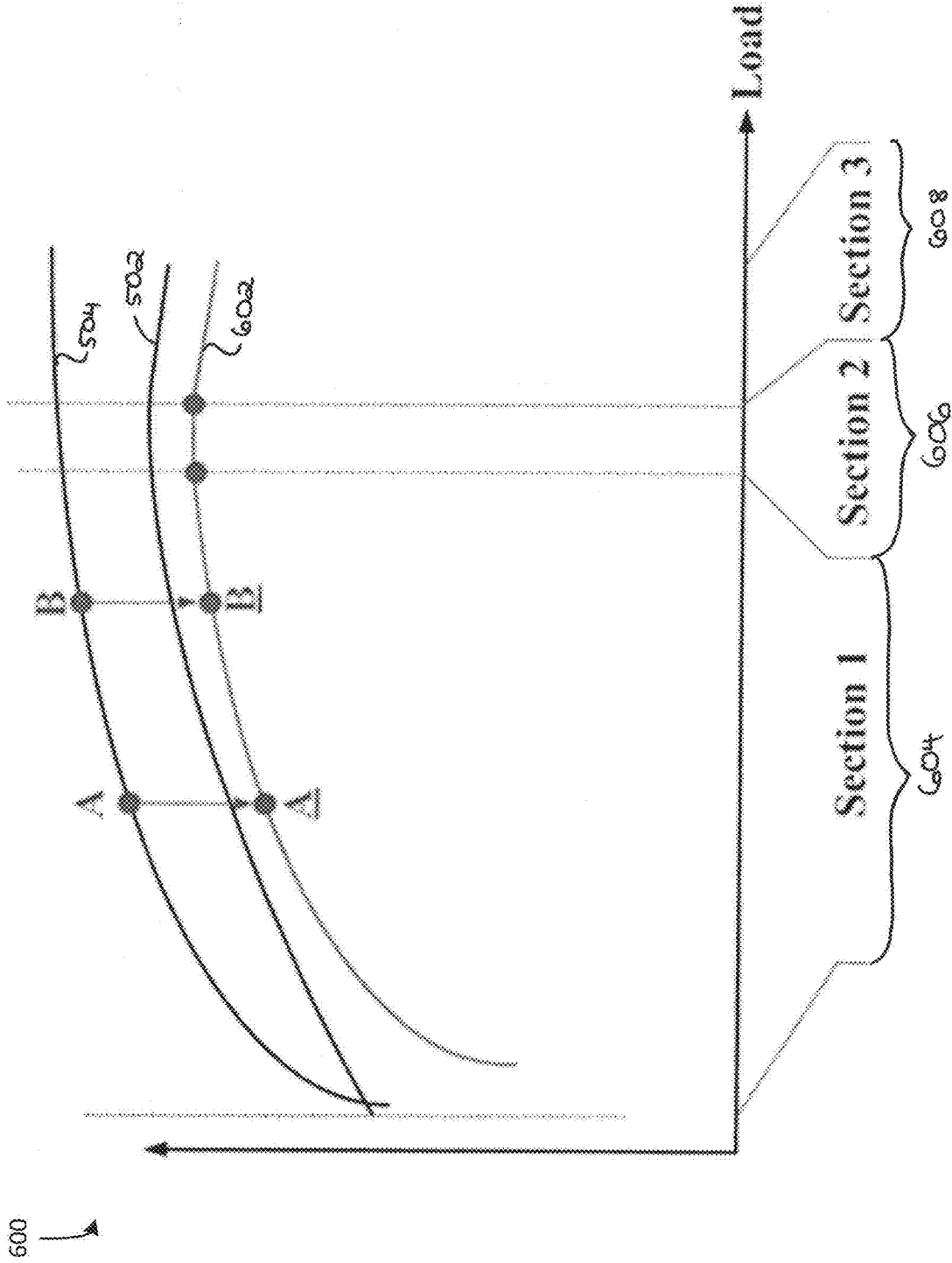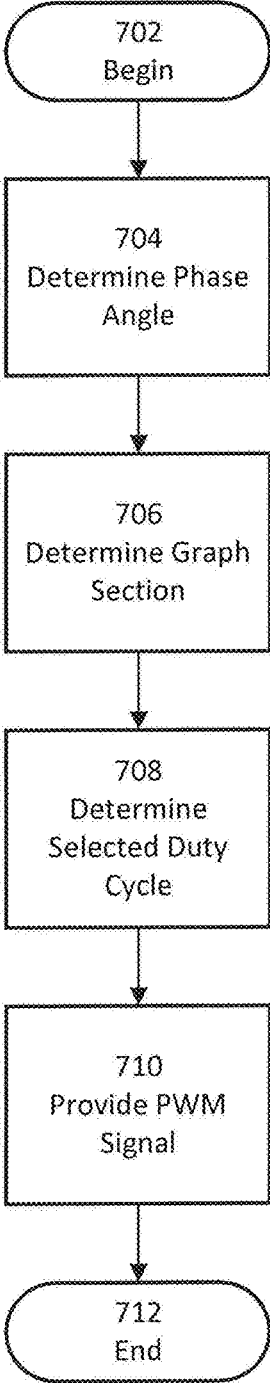
FIG. 7

SYSTEM AND METHOD FOR IMPROVING CONVERTER EFFICIENCY

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application Ser. No. 62/849,200 titled "SYSTEM AND METHOD FOR IMPROVING CONVERTER EFFICIENCY," filed on May 17, 2019, which is hereby incorporated by reference in its entirety.

BACKGROUND

1. Field of the Disclosure

[0002] At least one example in accordance with the present disclosure relates generally to power converters.

2. Discussion of Related Art

[0003] The use of power devices, such as power converters, is generally known. Power converters are configured to convert power from one state to another. For example, a resonant converter is one example of a power converter that may be configured to convert power from one state to another. A resonant converter includes capacitors and inductors tuned to resonate at a desirable frequency, and may convert direct current power into output power for provision to a load.

SUMMARY

[0004] According to at least one example of the disclosure, a converter system is provided including a primary-side circuit configured to be coupled to an energy source, a secondary-side circuit configured to be coupled to a load, the secondary-side circuit including an energy storage device and at least one switching device configured to control a load current provided by the energy storage device to the load, and a controller configured to be coupled to the primary-side circuit and the secondary-side circuit, the controller being further configured to determine a parameter indicative of an energy level of the energy storage device, and control, based on the parameter indicating that the energy level of the energy storage device is below a discharge energy level, the at least one switching device to be in an open and non-conducting position.

[0005] In at least one example, the converter system further includes a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, wherein the energy storage device includes the at least one secondary coil. In some examples, the at least one secondary coil is configured to provide an output current including the load current. In various examples, the converter system includes a current detection circuit configured to detect a value of an output current provided by the at least one secondary coil.

[0006] In at least one example, the controller is further configured to determine whether a value of an output current is below a current value corresponding to the discharge energy level of the energy storage device, and control the at least one switching device to be in the open and non-conducting position responsive to determining that the value of the output current is below the current value corresponding to the discharge energy level of the energy storage device. In some examples, the parameter includes a value of

an output current provided by the at least one secondary coil. In various examples, the primary-side circuit further comprises a plurality of switching devices configured to control an input current through the primary coil. In at least one example, the controller is further configured to determine a phase angle between the plurality of switching devices, and determine a duty cycle of the at least one switching device based on the phase angle between the plurality of switching devices. In some examples, the parameter includes the phase angle between the plurality of switching devices.

[0007] According to another example of the disclosure, a non-transitory computer-readable medium storing thereon sequences of computer-executable instructions for controlling a converter system having a primary-side circuit, a secondary-side circuit, an energy storage device, and at least one switching device configured to control a load current provided by the energy storage device to a load is provided, the sequences of computer-executable instructions including instructions that instruct at least one processor to determine a parameter indicative of an energy level of the energy storage device, and control, based on the parameter indicating that the energy level of the energy storage device is below a discharge energy level, the at least one switching device to be in an open and non-conducting position.

[0008] In at least one example, the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, the energy storage device including the at least one secondary coil, and the at least one secondary coil being configured to provide an output current including the load current, and wherein the instructions further instruct the at least one processor to detect a value of the output current provided by the at least one secondary coil. In some examples, the instructions are further configured to instruct the at least one processor to determine whether a value of an output current is below a current value corresponding to the discharge energy level of the energy storage device, and control the at least one switching device to be in the open and non-conducting position responsive to determining that the value of the output current is below the current value corresponding to the discharge energy level of the energy storage device.

[0009] In various examples, the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, the energy storage device including the at least one secondary coil, and wherein the parameter includes a value of an output current provided by the at least one secondary coil. In some examples, the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit, the primary-side circuit further comprising a plurality of switching devices configured to control an input current through the primary-side circuit, and at least one secondary coil coupled to the secondary-side circuit, and wherein the instructions further instruct the at least one processor to determine a phase angle between the plurality of switching devices, and determine a duty cycle of the at least one switching device based on the phase angle between the plurality of switching devices. In various examples, the parameter includes the phase angle between the plurality of switching devices.

[0010] According to another example of the disclosure, a method of controlling a converter system having a primary-side circuit, a secondary-side circuit, an energy storage

device, and at least one switching device configured to control a load current provided by the energy storage device to a load is provided, the method comprising determining a parameter indicative of an energy level of the energy storage device, and controlling, based on the parameter indicating that the energy level of the energy storage device is below a discharge energy level, the at least one switching device to be in an open and non-conducting position.

[0011] In at least one example, the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, the energy storage device including the at least one secondary coil, and the at least one secondary coil being configured to provide an output current including the load current, and wherein the method further comprises detecting a value of the output current provided by the at least one secondary coil. In various examples, the method further comprises determining whether a value of an output current is below a current value corresponding to the discharge energy level of the energy storage device, and controlling the at least one switching device to be in the open and non-conducting position responsive to determining that the value of the output current is below the current value corresponding to the discharge energy level of the energy storage device, wherein the parameter includes the value of the output current.

[0012] In various examples, the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit, the primary-side circuit further comprising a plurality of switching devices configured to control an input current through the primary-side circuit, and at least one secondary coil coupled to the secondary-side circuit, and the method further comprises determining a phase angle between the plurality of switching devices, and determining a duty cycle of the at least one switching device based on the phase angle between the plurality of switching devices. In at least one example, the parameter includes the phase angle between the plurality of switching devices.

[0013] According to at least one aspect of the present disclosure, a converter system is provided including a primary side configured to be coupled to an energy source, a secondary side configured to be coupled to a load, the secondary side including at least one switching device configured to control an output current provided to the load, and a controller configured to be coupled to the primary side and the secondary side, the controller being further configured to determine the output current provided to the load, and control, responsive to determining that the output current is zero, the at least one switching device to be in an open and non-conducting position.

[0014] According to another aspect of the present disclosure, a method of operating a converter including a primary side and a secondary side, the secondary side configured to be coupled to a load and including at least one switching device configured to control an output current provided to the load, the method including determining the output current provided to the load, and controlling, responsive to determining that the output current is zero, the at least one switching device to be in an open and non-conducting position.

[0015] According to another aspect of the present disclosure, a converter system is provided including a primary side configured to be coupled to an energy source, the primary side including at least two switching devices, a secondary side configured to be coupled to a load, the secondary side including at least one switching device configured to control an output current provided to the load, and a controller configured to be coupled to the primary side and the secondary side, the controller being further configured to determine a duty cycle phase angle of the at least two switching devices, determine, based on the duty cycle phase angle, a duty cycle of the at least one switching device, the duty cycle being longer than the duty cycle phase angle, and control the at least one switching device based on the duty cycle.

[0016] According to another aspect of the present disclosure, a method of operating a converter including a primary side including at least two switching devices, and a secondary side configured to be coupled to a load and including at least one switching device configured to control an output current provided to the load, the method including determining a duty cycle phase angle of the at least two switching devices, determining, based on the duty cycle phase angle, a duty cycle of the at least one switching device, the duty cycle being longer than the duty cycle phase angle, and controlling the at least one switching device based on the duty cycle.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide an illustration and a further understanding of the various aspects and embodiments, and are incorporated in and constitute a part of this specification, but are not intended as a definition of the limits of any particular embodiment. The drawings, together with the remainder of the specification, serve to explain principles and operations of the described and claimed aspects and embodiments. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. In the figures:

[0018] FIG. 1A illustrates a circuit diagram of a converter according to an example;

[0019] FIG. 1B illustrates a circuit diagram of the converter conducting a first current according to an example;

[0020] FIG. 1C illustrates a circuit diagram of the converter conducting a second current according to an example;

[0021] FIG. 2A illustrates a first timing diagram according to an example;

[0022] FIG. 2B illustrates a second timing diagram according to an example;

[0023] FIG. 2C illustrates a third timing diagram according to an example;

[0024] FIG. 3 illustrates a schematic diagram of a converter control circuit according to an example;

[0025] FIG. 4 illustrates a fourth timing diagram according to an example;

[0026] FIG. 5 illustrates a graph depicting a relationship between a phase angle and an optimal duty cycle according to an example;

[0027] FIG. 6 illustrates a graph depicting a relationship between a phase angle, an optimal duty cycle, and a selected duty cycle according to an example; and

[0028] FIG. 7 illustrates a process of controlling a converter according to an example.

DETAILED DESCRIPTION

[0029] Examples of the methods and systems discussed herein are not limited in application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The methods and systems are capable of implementation in other embodiments and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. In particular, acts, components, elements and features discussed in connection with any one or more examples are not intended to be excluded from a similar role in any other examples.

[0030] Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. Any references to examples, embodiments, components, elements or acts of the systems and methods herein referred to in the singular may also embrace embodiments including a plurality, and any references in plural to any embodiment, component, element or act herein may also embrace embodiments including only a singularity. References in the singular or plural form are no intended to limit the presently disclosed systems or methods, their components, acts, or elements. The use herein of "including," "comprising," "having," "containing," "involving," and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

[0031] References to "or" may be construed as inclusive so that any terms described using "or" may indicate any of a single, more than one, and all of the described terms. In addition, in the event of inconsistent usages of terms between this document and documents incorporated herein by reference, the term usage in the incorporated features is supplementary to that of this document; for irreconcilable differences, the term usage in this document controls.

[0032] Power converters are configured to convert power from one state to another. An example of a power converter is a resonant converter, which includes capacitors and inductors tuned to a particular resonant frequency. In one example, a resonant converter may convert power received from a direct current (DC) power source into output power.

[0033] In practical implementations, a resonant converter is not perfectly efficient. For example, power may be consumed by the resonant converter in converting DC power received from the DC power source into output power. It may be advantageous to increase the efficiency of a resonant converter by reducing an amount of power consumed by the resonant converter in converting input power into output power.

[0034] As discussed above, certain resonant converters include capacitors and inductors. For example, resonant converters may include a transformer having a primary coil and at least one secondary coil. A magnetic field may be induced in the primary coil by an energy source, such as a battery. A magnetic field induced in the primary coil induces a magnetic field in the at least one secondary coil, which induces a current through the at least one secondary coil. For example, the induced current may be discharged to a load through a switching device. The switching device may control the induced current by modulating a state (that is, open and non-conducting or closed and conducting) of the switching device.

[0035] In some converters, a secondary coil may be prevented from fully discharging stored energy to a load. For example, a switching device configured to control the induced current may be opened before the secondary coil has fully discharged. The remaining energy stored by the secondary coil after the storage device is opened may be wasted and thereby lower the efficiency of the converter. An efficiency of a resonant converter may therefore be increased by enabling one or more secondary coils in a resonant converter to fully discharge before a switching device connected thereto is opened.

[0036] In a first example, a current detected by a current detection circuit is implemented to determine an output current provided to a load by an energy storage device (for example, a secondary coil of a transformer) via a switching device. As the energy storage device discharges, the output current provided by the energy storage device via the switching device may decrease. That is, a remaining energy level of the energy storage device may decrease in proportion to the discharge current. The switching device is maintained in a closed and conducting position until a determination is made by the current detection circuit that the output current is at or below a selected current value, at which point the switching device is opened. The selected current value may correspond to a substantially discharged energy level of the energy storage device. Thus, the efficiency of the resonant converter may be improved by ensuring that a desired amount of energy stored by the energy storage device is discharged to a load.

[0037] In a second example, a control method is implemented to operate a switching device configured to control an output current provided by an energy storage device to a load. The control method may include identifying a parameter corresponding to a duty cycle of the switching device. An optimal value of the parameter corresponding to the duty cycle is determined, where the optimal value may correspond to maintaining the switching device in a closed and conducting position until the energy storage device has substantially discharged. The switching device is thus controlled pursuant to the parameter corresponding to the duty cycle. Thus, the efficiency of the resonant converter may be improved by ensuring that energy stored by the energy storage device is fully discharged to a load.

[0038] FIG. 1A illustrates a resonant converter 100. The resonant converter 100 may be implemented in a power device. In one example, the resonant converter 100 may be implemented in a DC power supply configured to be coupled to a load, and may be configured to convert DC power in a first state into DC power in a second state.

[0039] The resonant converter 100 includes a primary-side circuit 102 coupled to a secondary-side circuit 104 via a transformer 106. The transformer 106 includes a primary coil 108, a first secondary coil 110a, and a second secondary coil 110b. The primary-side circuit 102 includes components coupled to the primary coil 108, which may include an energy source 112, a first switching device 114a, a second switching device 114b, a third switching device 114c, a fourth switching device 114d, a first inductor 116, a second inductor 118, and a capacitor 120, and may include the primary coil 108. The secondary-side circuit 104 includes components coupled to the secondary coils 110a, 110b, which may include a fifth switching device 122a, a sixth

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switching device **122***b*, and a capacitor **124**, and may include the first secondary coil **110***a* and the second secondary coil **110***b*.

[0040] In some embodiments, the primary-side circuit **102** may be coupled to the energy source **112**, but may not include the energy source **112**. The secondary-side circuit **104** may be configured to be coupled to a load **126**. In one example, the resonant converter **100** is coupled to a controller **128** configured to control the switching devices **114**, **122**. In another example, the resonant converter **100** includes the controller **128**.

[0041] The resonant converter **100** is configured to receive input power from the energy source **112**, convert the input power into output power, and provide the output power to the load **126**. The controller **128** controls operation of the resonant converter **100** by modulating a respective state of each of the switching devices **114**, **122**. Power provided to the transformer **106** may be controlled by transmitting pulse width modulation (PWM) signals from the controller **128** to control connections (for example, gates) of the switching devices **114**, **122**.

[0042] FIG. 2A illustrates a timing diagram **200***a* of PWM signals **202-212** provided by the controller **128** to the switching devices **114**, **122** while the resonant converter **100** is in a standby mode of operation according to an example. The timing diagram **200***a* includes a first PWM signal **202**, a second PWM signal **204**, a third PWM signal **206**, a fourth PWM signal **208**, a fifth PWM signal **210**, and a sixth PWM signal **212**. The first PWM signal **202** is provided to the first switching device **114***a*, the second PWM signal **204** is provided to the second switching device **114***b*, the third PWM signal **206** is provided to the third switching device **114***c*, the fourth PWM signal **208** is provided to the fourth switching device **114***d*, the fifth PWM signal **210** is provided to the fifth switching device **122***a*, and the sixth PWM signal **212** is provided to the sixth switching device **122***b*. In one example, a logical HIGH level of the signals **202-212** controls the respective switching devices to be in a closed and conducting state, and a logical LOW level of the signals **202-212** controls the respective switching devices to be in an open and non-conducting state.

[0043] The resonant converter **100** may be in the standby mode of operation where the load **126** is not drawing power. Thus, no appreciable amount of power is provided to the load **126** while the resonant converter **100** is in the standby mode of operation. As illustrated by the timing diagram **200***a*, the PWM signals **202**, **208** are simultaneously HIGH during a first period of time **214**, the PWM signals **204**, **206** are simultaneously HIGH at during a second period of time **216**, and the PWM signals **210**, **212** are LOW during both the first period of time **214** and the second period of time **216**.

[0044] During the first period of time **214**, therefore, the first switching device **114***a* and the fourth switching device **114***d* are in a closed and conducting position, and the second switching device **114***b* and the third switching device **114***c* are in an open and non-conducting position. Thus, no conductive path through which power may be provided from the energy source **112** to the transformer **106** is present. Furthermore, the switching devices **122** remain in an open and non-conducting position.

[0045] After the first period of time **214**, the second period of time **216** begins. During the second period of time **216**, the first switching device **114***a* and the fourth switching

device **114***d* are in an open and non-conducting position, and the second switching device **114***b* and the third switching device **114***c* are in a closed and conducting position. Thus, no conductive path through which power may be provided from the energy source **112** to the transformer **106** is present. Furthermore, the switching devices **122** remain in an open and non-conducting position.

[0046] After the second period of time **216**, the PWM signals **202**, **208** are again simultaneously HIGH as during the first period of time **214**. A cycle is established whereby the PWM signals **202**, **208** are simultaneously HIGH, followed by the PWM signals **204**, **206** being simultaneously HIGH, and so forth, without any appreciable power being provided to the load **126** as long as the resonant converter **100** is in the standby mode of operation.

[0047] FIG. 2B illustrates a timing diagram **200***b* of PWM signals provided by the controller **128** while the resonant converter **100** transitions from the standby mode of operation to an active mode of operation according to an example. The resonant converter **100** transitions from the standby mode of operation to the active mode of operation at a first time **222**. Before the first time **222**, the resonant converter **100** is in a standby mode of operation. After the first time **222**, the resonant converter **100** transitions to the active mode of operation. The timing diagram **200***b* includes a primary-side current trace **218** indicative of a current output by the energy source **112**, and a secondary-side current trace **220** indicative of a current provided to the load **126**.

[0048] As the resonant converter **100** transitions to the active mode of operation after the first time **222**, the second PWM signal **204** is no longer entirely in phase with the third PWM signal **206**. The third PWM signal **206** is delayed relative to the second PWM signal **204** and overlaps temporally with (that is, is at a logical HIGH level simultaneously with) the first PWM signal **202**, the overlap being indicated by a phase angle **224**. A rising edge of the sixth PWM signal **212** coincides with a rising edge of the first PWM signal **202**, and a falling edge of the sixth PWM signal **212** coincides with a falling edge of the third PWM signal **206**. Similarly, a rising edge of the fifth PWM signal **210** coincides with a rising edge of the second PWM signal **204**, and a falling edge of the fifth PWM signal **210** coincides with a falling edge of the fourth PWM signal **208** (not illustrated).

[0049] Accordingly, during the temporal overlap indicated by the phase angle **224**, generally referred to as a first power cycle, the first switching device **114***a*, the third switching device **114***c*, and the sixth switching device **122***b* are controlled to be in a closed and conducting position. The energy source **112** is therefore enabled to provide a current indicated by the primary-side current trace **218** to a conductive path including the energy source **112**, the first switching device **114***a*, the first inductor **116**, the primary coil **108**, the capacitor **120**, and the third switching device **114***c*. FIG. 1B illustrates an example of the resonant converter **100** during the first power cycle, in which the primary-side circuit **102** of the resonant converter **100** conducts a first primary-side current **130**, a value of which is indicated by the primary-side current trace **218**, and the secondary-side circuit **104** of the resonant converter **100** conducts a first secondary-side current **132**, a value of which is indicated by the secondary-side current trace **220**.

[0050] The first primary-side current **130** is conducted by the primary coil **108**, which induces a voltage across the first

secondary coil **110***a* and the second secondary coil **110***b*. Because the sixth switching device **122***b* is in a closed and conducting position, the first secondary-side current **132** is induced in the secondary-side circuit **104** in a conductive path including the second secondary coil **110***b*, the capacitor **124**, the load **126**, and the sixth switching device **122***b*. The first secondary-side current **132** thus indicates a current including a first portion that is provided to the load **126**, and a second portion that is provided to the capacitor **124**, via the sixth switching device **122***b*.

[0051] At the end of the first power cycle, the third switching device **114***c* and the sixth switching device **122***b* are opened approximately simultaneously. Opening the sixth switching device **122***b* simultaneously with the third switching device **114***c* may be disadvantageous, at least because energy may still be stored in the transformer **106**. The energy stored in the transformer **106** cannot be efficiently output to the load **126** if the sixth switching device **122***b* is in an open position. As indicated by the secondary-side current trace **220**, the first secondary-side current **132** persists after the switching devices **114***c*, **122***b* are opened as the transformer **106** discharges stored energy. However, the first secondary-side current **132** may be inefficiently discharged to the load **126** if the sixth switching device **122***b* is in an open and non-conducting position. For example, the output current may follow an inefficient discharge path including the intrinsic parallel-connected diode of the sixth switching device **122***b*. Thus, if the sixth switching device **122***b* is opened before the transformer **106** fully discharges, the efficiency of the resonant converter **100** may be disadvantageously lowered, at least due to electrical losses in the intrinsic parallel-connected diode of the sixth switching device **122***b*.

[0052] FIG. 1C illustrates an example of the resonant converter **100** during a second power cycle. In the second power cycle, not illustrated by the timing diagram **200***b*, the second switching device **114***b*, the fourth switching device **114***d*, and the fifth switching device **122***a* are controlled to be in a closed and conducting position. The energy source **112** discharges power to a conductive path including the energy source **112**, the second switching device **114***b*, the first inductor **116**, the primary coil **108**, the capacitor **120**, and the fourth switching device **114***d*.

[0053] A second primary-side current **134** is conducted by the primary coil **108**, which induces a voltage across the first secondary coil **110***a* and the second secondary coil **110***b*. Because the fifth switching device **122***a* is in a closed and conducting position, a second secondary-side current **136** is induced in the secondary-side circuit **104** in a conductive path including the first secondary coil **110***a*, the capacitor **124**, the load **126**, and the fifth switching device **122***a*.

[0054] At the end of the second power cycle, the fourth switching device **114***d* may be opened. The fifth switching device **122***a* may be opened simultaneously with the fourth switching device **114***d*. Opening the fifth switching device **122***a* simultaneously with the fourth switching device **114***d* may be disadvantageous, at least because energy may still be stored in the transformer **106**. The energy stored in the transformer **106** cannot be efficiently output to the load **126** if the fifth switching device **122***a* is in an open position. Thus, if the fifth switching device **122***a* is opened before the transformer **106** fully discharges, the efficiency of the resonant converter **100** may be disadvantageously lowered.

[0055] In light of the foregoing deficiencies, it may be advantageous to extend a respective duty cycle of the switching devices **122** to enable the transformer **106** to discharge stored energy more efficiently. For example, FIG. 2C illustrates a timing diagram **200***c* illustrating an advantageous duty cycle of the switching devices **122**. As illustrated by the sixth PWM signal **212**, the duty cycle of the sixth switching device **122***b* is extended until the output current is approximately zero, rather than transitioning to a logical LOW level simultaneously with the third PWM signal **206**. Similarly, as illustrated by the fifth PWM signal **210**, the duty cycle of the fifth switching device **122***a* is extended until the output current is approximately zero, rather than transitioning to a logical LOW level simultaneously with the fourth PWM signal **208**.

[0056] Accordingly, it may be advantageous to extend the duty cycles of the switching devices **122**, relative to prior solutions, in a manner illustrated by FIG. 2C. Two examples of implementing the extended duty cycles are provided. In a first example, a circuit is implemented to determine the output current provided to the load **126** and, responsive to determining that the output current is below a selected current value, the switching devices **122** are opened. In a second example, a control method is implemented to determine a parameter indicative of an optimal duty cycle of the switching devices **122**. For example, the parameter may be a phase angle indicative of an overlap between the phases of the switching devices **114***a*, **114***c* or an overlap between the phases of the switching devices **114***b*, **114***d*. The parameter is analyzed by the controller **128** to determine an optimal duty cycle of the switching devices **122**, pursuant to which the switching devices **122** are controlled.

[0057] The first example of implementing the extended duty cycle discussed above will now be discussed in greater detail. FIG. 3 illustrates a schematic diagram of a converter control circuit **300**. The converter control circuit **300** includes a current detection circuit **302**, a first logic gate **304**, and a second logic gate **306**. In one example, the converter control circuit **300** is configured to receive the first PWM signal **202** and the second PWM signal **204** from the controller **128**, and is configured to provide the fifth PWM signal **210** and the sixth PWM signal **212** to the fifth switching device **122***a* and the sixth switching device **122***b*, respectively. In another example, the converter control circuit **300** may include, or be included by, the controller **128**.

[0058] The current detection circuit **302** is configured to detect an output current provided to the load **126** (for example, the first secondary-side current **132** or the second secondary-side current **134**) and output, based on the output current, a current detection signal **308** to the logic gates **304**, **306**. As discussed in greater detail below, the current detection signal **308** may be a square wave having a first value (for example, a logical LOW level) where the output current is below a selected current value, and a second value (for example, a logical HIGH level) where the output current is above the selected current value. For example, the output current may be below the selected current value where the transformer **106** has been approximately fully discharged, and the output current may be above the selected current value where the transformer **106** is still discharging.

[0059] The first logic gate **304** is configured to receive the second PWM signal **204** and the current detection signal **308**, and the second logic gate **306** is configured to receive the first PWM signal **202** and the current detection signal **308**. The first logic gate **304** is configured to output the fifth PWM signal **210** based on the second PWM signal **204** and

the current detection signal **308**, and the second logic gate **306** is configured to output the sixth PWM signal **212** based on the first PWM signal **202** and the current detection signal **308**.

[0060] In one example, the first logic gate **304** and the second logic gate **306** are AND gates. In this example, therefore, the first logic gate **304** is configured to output the fifth PWM signal **210** at a logical HIGH level when the current detection signal **308** and the second PWM signal **204** are simultaneously at a logical HIGH level, and is configured to output the fifth PWM signal **210** at a logical LOW level when either or both of the current detection signal **308** and the second PWM signal **204** are at a logical LOW level. Similarly, the second logic gate **306** is configured to output the sixth PWM signal **212** at a logical HIGH level when the current detection signal **308** and the first PWM signal **202** are at a logical HIGH level, and is configured to output the sixth PWM signal **212** at a logical LOW level when either or both of the current detection signal **308** and the first PWM signal **202** are at a logical LOW level.

[0061] Thus, in this example, the fifth PWM signal **210** may be at a logical HIGH level where the second PWM signal **204** is at a logical HIGH level and the output current provided to the load **126** is above a selected current value (for example, a value corresponding to a situation in which the transformer **106** is still discharging), and the sixth PWM signal **212** is at a logical HIGH level where the first PWM signal **202** is at a logical HIGH level and the output current provided to the load **126** is above a selected current value. FIG. **4** illustrates a timing diagram **400** according to this example, in which the current detection signal **308** is generated having a first value indicative of an output current above a selected current value, the output current being indicated by the secondary-side current trace **220**, and having a second value indicative of an output current below the selected current value. For example, the first value indicative of the output current above the selected current value may be a logical HIGH value, and the second value indicative of the output current being below the selected current value may be a logical LOW value, as illustrated by FIG. **4**. Thus, in contrast to prior implementations, the fifth PWM signal **210** is not dependent upon a state of the fourth PWM signal **208**, and the sixth PWM signal **212** is not dependent upon a state of the third PWM signal **206**.

[0062] As discussed above, the current detection circuit **302** is configured to detect an output current provided to the load **126** and output, based on the output current, the current detection signal **308** to the logic gates **304**, **306**. The current detection circuit **302** may include, or be otherwise communicatively coupled to, one or more sensors configured to sense parameters indicative of the output current provided to the load **126**. For example, the current detection circuit **302** and/or the controller **128** may include, or be otherwise communicatively coupled to, one or more ammeters and/or voltmeters configured to sense a current or voltage, respectively, indicative of the output current provided to the load **126**. As discussed above, the current detection circuit **302** is further configured to output the current detection signal **308** having a first value where the output current determined by the current detection circuit **302** is below a selected current value, and a second value where the output current determined by the current detection circuit **302** is above the selected current value.

[0063] The second example of implementing the extended duty cycle will now be discussed in greater detail. The second example includes a control method which may be implemented to determine a parameter indicative of an optimal duty cycle of the switching devices **122**, rather than determining the output current. A parameter indicative of the optimal duty cycle may be a phase angle indicative of an overlap between the first PWM signal **202** and the third PWM signal **206** and/or the second PWM signal **204** and the fourth PWM signal **208**.

[0064] For example, and with reference to FIG. **2C**, a first phase angle **226** may include an overlap between the first PWM signal **202** and the third PWM signal **206**. The first phase angle **226** may be analyzed to determine an optimal duty cycle of the sixth PWM signal **212**. Similarly, a second phase angle **228** may include an overlap between the second PWM signal **204** and the fourth PWM signal **208**. The second phase angle **228** may be analyzed to determine an optimal duty cycle of the fifth PWM signal **210**.

[0065] FIG. **5** illustrates a graph **500** depicting a relationship between a phase angle (for example, the first phase angle **226** or the second phase angle **228**) and an optimal duty cycle (for example, of the fifth PWM signal **210** or the sixth PWM signal **212**). The graph **500** includes an optimal duty cycle trace **502**, a phase angle trace **504**, an input current trace **506**, and an output current trace **508**. The optimal duty cycle trace **502** is indicative of an optimal phase by which to extend the fifth PWM signal **210** and/or the sixth PWM signal **212** beyond a falling edge of the third PWM signal **206** and/or a falling edge of the fourth PWM signal **208**. The phase angle trace **504** is indicative of the first phase angle **226** (for example, where the optimal duty cycle trace **502** is indicative of the sixth PWM signal **212**) and/or the second phase angle **228** (for example, where the optimal duty cycle trace **502** is indicative of the fifth PWM signal **210**). The input current trace **506** is indicative of a current received from the energy source **112** (for example, the first primary-side current **130** or the second primary-side current **134**). The output current trace **508** is indicative of an output current, a portion of which is provided to the load **126** (for example, the first secondary-side current **132** or the second secondary-side current **136**).

[0066] As indicated by the graph **500**, a relationship between the optimal duty cycle trace **502** and the phase angle trace **504** varies as the output current trace **508** increases, indicative of the load **126** increasing and thereby drawing more output current. Accordingly, in determining the optimal duty cycle trace **502** based on the phase angle trace **504**, the optimal duty cycle trace **502** and the phase angle trace **504** may be divided into several sections, each section corresponding to a respective relationship between the optimal duty cycle trace **502** and the phase angle trace **504**.

[0067] FIG. **6** illustrates a graph **600** depicting a relationship between a phase angle, an optimal duty cycle, and a selected duty cycle. The graph **600** includes the optimal duty cycle trace **502**, the phase angle trace **504**, and a selected duty cycle trace **602**. The selected duty cycle trace **602** is indicative of a selected duty cycle that is determined by the controller **128** and actually provided by the controller **128** to one of the switching devices **122**.

[0068] As discussed above, the optimal duty cycle trace **502** is indicative of an ideal duty cycle. However, it may be computationally infeasible or undesirable to precisely cal-

culate the optimal duty cycle trace **502** in some examples. Accordingly, rather than directly determining the optimal duty cycle trace **502** from the phase angle trace **504**, the selected duty cycle trace **602** may be determined based on the phase angle trace **504** as an approximation of the optimal duty cycle trace **502**.

[0069] The graph **600** is divided into a first section **604**, a second section **606**, and a third section **608**. Each section corresponds to a respective relationship between the phase angle trace **504** and the optimal duty cycle trace **502** and the selected duty cycle trace **602**. In the first section **604**, the optimal duty cycle trace **502** and the selected duty cycle **602** increase as the output current provided to the load **126** increases. In the second section **606**, the optimal duty cycle trace **502** and the selected duty cycle trace **602** are approximately constant. In the third section **608**, the optimal duty cycle trace **502** and the selected duty cycle trace **602** decrease as the output current provided to the load **126** increases.

[0070] A method of determining a selected duty cycle trace based on the phase angle trace **504** varies for each section. In the first section **604**, the selected duty cycle trace **602** is determined by multiplying the phase angle trace **504** by a first constant value. In the second section **606**, the selected duty cycle trace **602** is determined to be set to a second constant value. In the third section **608**, the selected duty cycle trace **602** is determined by multiplying the phase angle trace **504** by a third constant value.

[0071] The first, second, and third constant values may be stored in storage accessible to the controller **128**. For example, the first and third constant values may be determined experimentally by identifying constant values that, when multiplied by the phase angle trace **504**, yields a selected duty cycle that most accurately represents the optimal duty cycle trace **502**. The second constant value may be determined experimentally by determining a constant value that most accurately represents the optimal duty cycle trace **502**.

[0072] FIG. 7 illustrates a process **700** of determining the selected duty cycle indicated by the selected duty cycle trace **602** based on the phase angle indicated by the phase angle trace **504**. The process **700** may be executed by the controller **128**. The process **700** includes acts of determining a phase angle, determining a section of the graph **600** to which the phase angle corresponds, determining a selected duty cycle, and providing a PWM signal with the selected duty cycle to a switching device.

[0073] At act **702**, the process **700** begins. At act **704**, a phase angle is determined. As discussed above, the first phase angle **226** may correspond to an overlap between the first PWM signal **202** and the third PWM signal **206** provided by the controller **128**, and the second phase angle **228** may correspond to an overlap between the second PWM signal **204** and the fourth PWM signal **208** provided by the controller **128**. Accordingly, the controller **128** may determine the phase angle at act **704** by determining a phase overlap between the signals **202**, **206** and/or the signals **204**, **208**.

[0074] At act **706**, a section of the graph **600** to which the phase angle corresponds is determined. The controller **128** may determine where the phase angle determined at act **704** is along the phase angle trace **504** and, based on the determination, determine which of the sections **604-608** the

phase angle corresponds to. As discussed above, each of the sections **604-608** correspond to a respective range of phase angle values.

[0075] At act **708**, a selected duty cycle is determined based on a section of the graph **600** to which the phase angle corresponds. For example, if the phase angle corresponds to the first section **604**, then the phase angle determined at act **704** may be multiplied by the first constant value to determine the selected duty cycle. If the phase angle corresponds to the second section **606**, then the selected duty cycle may be set to the second constant value. If the phase angle corresponds to the third section **608**, then the phase angle may be multiplied by the third constant value to determine the selected duty cycle.

[0076] At **710**, a PWM signal is provided to a switching device based on the selected duty cycle. For example, where the phase angle is the first phase angle **226**, then the selected duty cycle is used to determine the sixth PWM signal **212**. More particularly, the sixth PWM signal **212** may be generated by extending the first phase angle **226** by the selected duty cycle. Similarly, where the phase angle is the second phase angle **228**, the fifth PWM signal **210** is determined by extending the second phase angle **228** by the selected duty cycle. The fifth PWM signal **210** and/or the sixth PWM signal **212** are provided to the switching devices **122a**, **122b**, respectively. At act **712**, the process **700** ends.

[0077] The process **700** may be repeatedly executed by the controller **128**. For example, the controller **128** may execute the process **700** at a specific frequency (for example, 80 kHz). Thus, the phase angles **226**, **228** may be repeatedly re-evaluated to determine the PWM signals **210**, **212** and thereby maximize an efficiency of the resonant converter **100**.

[0078] Although the PWM signals **210**, **212** have been determined based on the phase angles **226**, **228** in the foregoing examples, in other embodiments, other parameters may be analyzed to determine the PWM signals **210**, **212**. For example, the controller **128** may determine the PWM signals **210**, **212** based on the input current provided by the energy source **112**, a current in the primary coil **108** or the secondary coils **110**, the output current provided to the load **126**, or any other parameter related to the duty cycle of the PWM signals **210**, **212**.

[0079] As discussed above, the current detection circuit **302** is configured to determine a current value and determine whether the current value is below a selected current value corresponding to an energy level of the transformer **106**. In some examples, the selected current value may be selected by a user, such as a designer of the resonant converter **100** or an end user of the resonant converter **100**. In other examples, the current detection circuit **302** and/or the controller **128** (which may include the current detection circuit **302**) may determine the selected current value dynamically. In various examples, the selected current value may be zero, or may be greater than zero.

[0080] Accordingly, examples have been provided in which a switching device configured to control an output current is controlled based on an energy storage device, such as a secondary coil of a transformer, being substantially discharged. An energy level of the energy storage device may be determined by determining a parameter indicative of the energy level of the energy storage device. In one example, the parameter indicative of the energy level includes the output current provided to the load. The output

current is measured and the switching device is opened responsive to determining that a value of the output current is below a selected current value threshold, where the selected current value threshold corresponds to an energy storage device discharge energy level. In another example, the parameter indicative of the energy level of the energy storage device includes a phase angle between a plurality of switching devices controlling an input current. An optimal duty cycle of the switching device is determined based on the phase angle between the plurality of switching devices, thereby controlling a discharge of the energy storage device. In these examples, although an energy level of the energy storage device is not directly measured, the energy level of the energy storage device may be determined based on other parameters to control the switching device. For example, an energy level of the energy storage device may be determined such that the switching device may be opened responsive to determining that the energy level is below a discharge energy level corresponding to the energy storage device being substantially discharged.

[0081] Having thus described several aspects of at least one embodiment, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of, and within the spirit and scope of, this disclosure. Accordingly, the foregoing description and drawings are by way of example only.

What is claimed is:

1. A converter system including:
   a primary-side circuit configured to be coupled to an energy source;
   a secondary-side circuit configured to be coupled to a load, the secondary-side circuit including an energy storage device and at least one switching device configured to control a load current provided by the energy storage device to the load; and
   a controller configured to be coupled to the primary-side circuit and the secondary-side circuit, the controller being further configured to:
      determine a parameter indicative of an energy level of the energy storage device; and
      control, based on the parameter indicating that the energy level of the energy storage device is below a discharge energy level, the at least one switching device to be in an open and non-conducting position.

2. The converter system of claim 1, further comprising a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, wherein the energy storage device includes the at least one secondary coil.

3. The converter system of claim 2, wherein the at least one secondary coil is configured to provide an output current including the load current.

4. The converter system of claim 2, further comprising a current detection circuit configured to detect a value of an output current provided by the at least one secondary coil.

5. The converter system of claim 2, wherein the controller is further configured to:
   determine whether a value of an output current is below a current value corresponding to the discharge energy level of the energy storage device; and
   control the at least one switching device to be in the open and non-conducting position responsive to determining

that the value of the output current is below the current value corresponding to the discharge energy level of the energy storage device.

6. The converter system of claim 2, wherein the parameter includes a value of an output current provided by the at least one secondary coil.

7. The converter system of claim 2, the primary-side circuit further comprising a plurality of switching devices configured to control an input current through the primary coil.

8. The converter system of claim 7, wherein the controller is further configured to:
   determine a phase angle between the plurality of switching devices; and
   determine a duty cycle of the at least one switching device based on the phase angle between the plurality of switching devices.

9. The converter system of claim 8, wherein the parameter includes the phase angle between the plurality of switching devices.

10. A non-transitory computer-readable medium storing thereon sequences of computer-executable instructions for controlling a converter system having a primary-side circuit, a secondary-side circuit, an energy storage device, and at least one switching device configured to control a load current provided by the energy storage device to a load, the sequences of computer-executable instructions including instructions that instruct at least one processor to:
   determine a parameter indicative of an energy level of the energy storage device; and
   control, based on the parameter indicating that the energy level of the energy storage device is below a discharge energy level, the at least one switching device to be in an open and non-conducting position.

11. The non-transitory computer-readable medium of claim 10, wherein the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, the energy storage device including the at least one secondary coil, and the at least one secondary coil being configured to provide an output current including the load current, and wherein the instructions further instruct the at least one processor to detect a value of the output current provided by the at least one secondary coil.

12. The non-transitory computer-readable medium of claim 10, wherein the instructions are further configured to instruct the at least one processor to:
   determine whether a value of an output current is below a current value corresponding to the discharge energy level of the energy storage device; and
   control the at least one switching device to be in the open and non-conducting position responsive to determining that the value of the output current is below the current value corresponding to the discharge energy level of the energy storage device.

13. The non-transitory computer-readable medium of claim 10, wherein the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, the energy storage device including the at least one secondary coil, and wherein the parameter includes a value of an output current provided by the at least one secondary coil.

14. The non-transitory computer-readable medium of claim **10**, wherein the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit, the primary-side circuit further comprising a plurality of switching devices configured to control an input current through the primary-side circuit, and at least one secondary coil coupled to the secondary-side circuit, and wherein the instructions further instruct the at least one processor to:

determine a phase angle between the plurality of switching devices; and

determine a duty cycle of the at least one switching device based on the phase angle between the plurality of switching devices.

15. The non-transitory computer-readable medium of claim **14**, wherein the parameter includes the phase angle between the plurality of switching devices.

16. A method of controlling a converter system having a primary-side circuit, a secondary-side circuit, an energy storage device, and at least one switching device configured to control a load current provided by the energy storage device to a load, the method comprising:

determining a parameter indicative of an energy level of the energy storage device; and

controlling, based on the parameter indicating that the energy level of the energy storage device is below a discharge energy level, the at least one switching device to be in an open and non-conducting position.

17. The method of claim **16**, wherein the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit and at least one secondary coil coupled to the secondary-side circuit, the energy storage device including the at least one secondary coil, and the at least one secondary coil being configured to provide an output current including the load current, and wherein the method further comprises detecting a value of the output current provided by the at least one secondary coil.

18. The method of claim **16**, further comprising:

determining whether a value of an output current is below a current value corresponding to the discharge energy level of the energy storage device; and

controlling the at least one switching device to be in the open and non-conducting position responsive to determining that the value of the output current is below the current value corresponding to the discharge energy level of the energy storage device,

wherein the parameter includes the value of the output current.

19. The method of claim **16**, wherein the converter system further comprises a transformer having a primary coil coupled to the primary-side circuit, the primary-side circuit further comprising a plurality of switching devices configured to control an input current through the primary-side circuit, and at least one secondary coil coupled to the secondary-side circuit, and wherein the method further comprises:

determining a phase angle between the plurality of switching devices; and

determining a duty cycle of the at least one switching device based on the phase angle between the plurality of switching devices.

20. The method of claim **19**, wherein the parameter includes the phase angle between the plurality of switching devices.

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