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(54) **RESONANT SWITCHING POWER CONVERTER WITH ADAPTIVE DEAD TIME CONTROL**

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USPC **363/21.03**; 363/97

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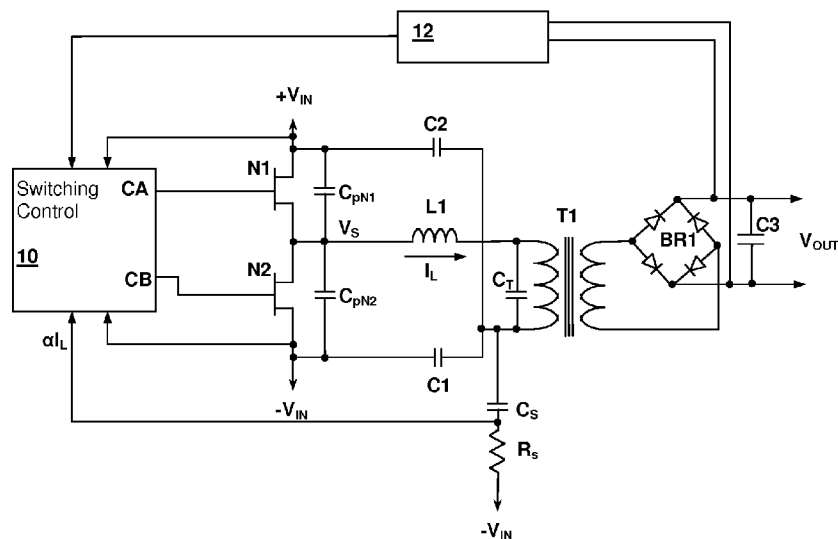*Primary Examiner* — Adolf Berhane
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(57)   **ABSTRACT**

A resonant switching power converter having adaptive dead time control provides improved efficiency along with reduced EMI/audible noise and component stresses. A dead time between pulses generated by a switching circuit is adaptively set in conformity with a value of the input voltage to the resonant switching power converter and an indication of a magnitude of the current passing through inductive element of the resonant tank of the converter. The indication of the current magnitude may be the switching frequency of the converter, or a measure of line or load current levels. The dead time can be obtained from a look-up table or computed from the current magnitude and input voltage values.

20 Claims, 3 Drawing Sheets

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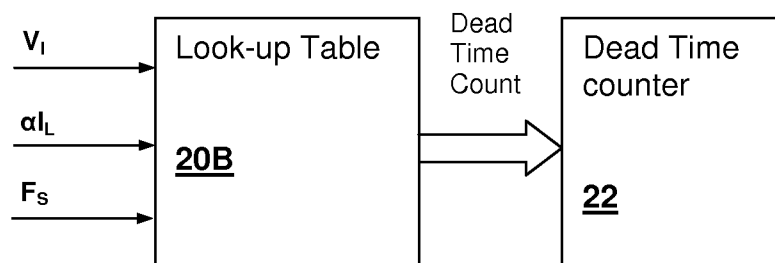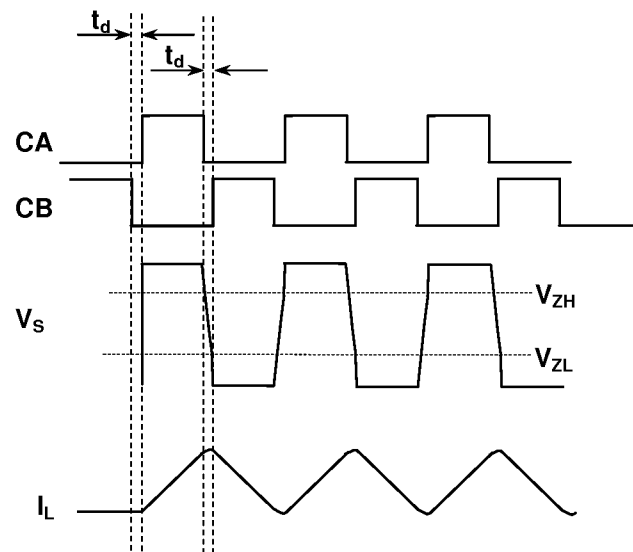
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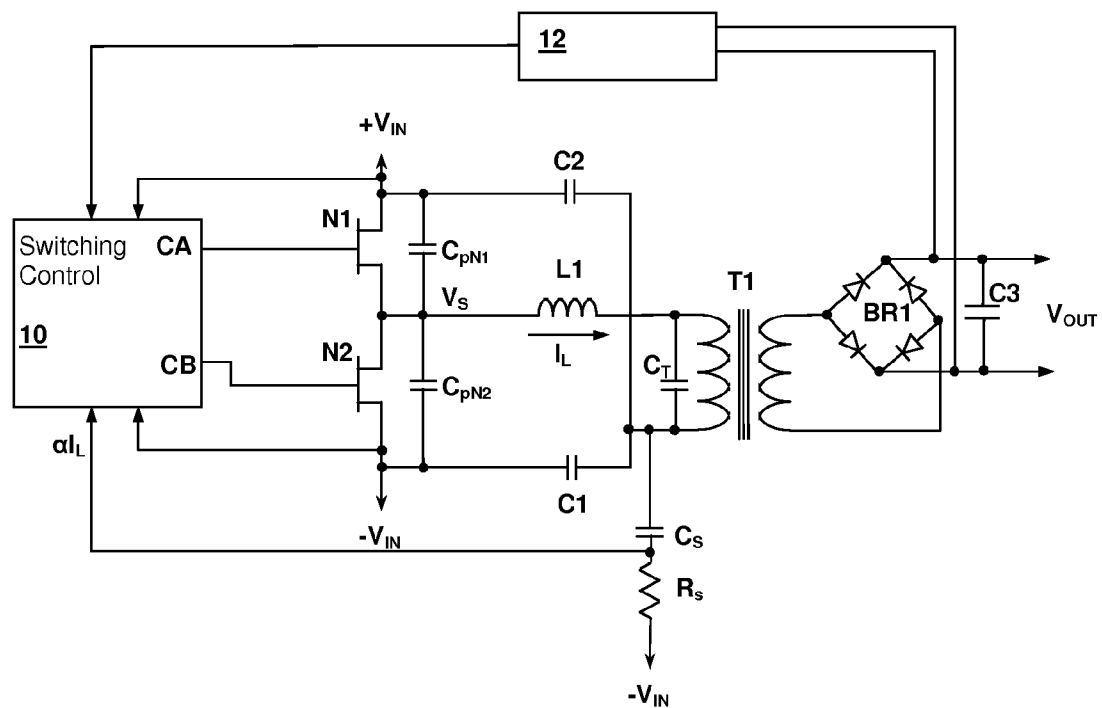
Fig. 1

V_I

αI_L

F_S

Computation
Block

20A

Dead
Time
Count

Dead Time
counter

22

Fig. 2A

V_I

αI_L

F_S

Look-up Table

20B

Dead
Time
Count

Dead Time
counter

22
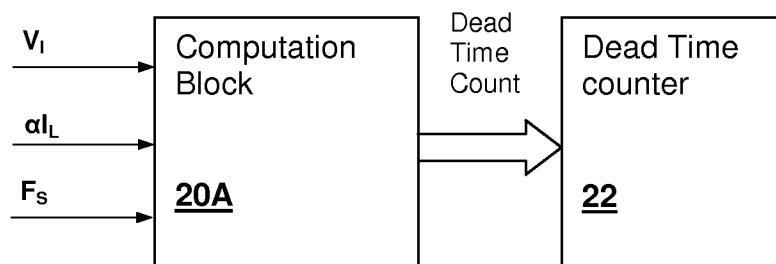
Fig. 2B

Fig. 3

RESONANT SWITCHING POWER CONVERTER WITH ADAPTIVE DEAD TIME CONTROL

This application Claims priority under 35 U.S.C. §119(e) to U.S. Provisional Patent Application Ser. No. 61/083,717 filed on Jul. 25, 2008.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to switching power regulator circuits, and more specifically, to a resonant switching power converter in which dead time between pulses is adaptively controlled.

2. Background of the Invention

In resonant switching power converters, to avoid introducing losses and stresses in the switching circuit, it is desirable to switch the transistors in the switching circuit when the voltage difference across the source and drain is at a minimum. Since any potential present across a switching transistor and any drain-source connected capacitor at the time of the transistor's activation will result in a waste of energy, zero-voltage switching (ZVS) control is desirable. If the switching circuit switches too early, the transistor and capacitors will be discharged through the switching circuit, wasting energy. However, if the switching circuit is switched too late, energy can be wasted by currents conducted through the body diodes of the transistors back to the power supply rail. ZVS control raises the efficiency of the power supply and also reduces the stresses experienced by the switching transistor, increasing reliability. Further, transients generated at the switching frequency can cause electromagnetic interference (EMI) and audible noise, as the switching frequency of such resonant converters is typically within the audio range.

In order to provide ZVS control, the dead time between pulses may be set to a time duration such that the input to the resonant tank has swung from near one power supply rail to the other power supply rail (for bipolar pulses), or has completed a full cycle (for unipolar pulses). However, since the frequency of the resonant converter is varied in order to control the inductor current and thus the energy supplied to the load, the time duration corresponding to the dead time will not be correct for all operating conditions. Typically the dead time is set to favor the higher power operating condition (i.e., the higher frequency operating condition), since losses due to non-optimum switching times are greater for higher inductor current levels.

Therefore, it would be desirable to provide a resonant switching power converter having improved efficiency, reduced stresses and audio/EMI noise.

SUMMARY OF THE INVENTION

The above stated objectives of providing a resonant switching power converter having improved efficiency, reduced stresses and reduced EMI and audible noise is achieved in a resonant switching power converter and its method of operation.

The resonant switching power converter includes a resonant tank circuit, a switching circuit for transferring energy to the resonant tank circuit from an input voltage source, and a transformer for coupling the resonant tank circuit to an output of the switching power converter. A dead time between pulses generated by the switching circuit is adaptively set, by a control circuit, in conformity with the voltage of the input

voltage and an indication of an inductor current passing through the inductive element of the resonant tank circuit.

The indication of the inductor current may be the switching frequency, a direct or indirect measurement of the current through the inductive element, or another related value such as output load current or an input line current of the power supply. The control circuit may compute the dead time on a cycle-by-cycle basis from the indication of the current, or use a look-up table that sets the dead time in conformity with the input voltage and inductor current values.

The foregoing and other objectives, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the invention, as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified schematic diagram depicting a resonant switching power converter in accordance with an embodiment of the present invention.

FIG. 2A and FIG. 2B are block diagrams depicting dead-time control circuits that may be used within switching control 10 of FIG. 1, in accordance with embodiments of the invention.

FIG. 3 is a timing diagram depicting operation of the switching power converter of FIG. 1.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENT

The present invention encompasses circuits and methods that adaptively control the dead-time between pulses in a resonant switching power converter in order to raise the efficiency of the converter and reduce stresses and audible/EMI noise. The dead-time is controlled in conformity with a value of the input voltage to the converter and an indication of the magnitude of the current flowing through an inductance of the resonant tank used within the resonant switching power converter.

Referring now to FIG. 1, a resonant switching power converter circuit in accordance with an embodiment of the present invention is shown. A switching control circuit 10 controls a switching circuit implemented by transistors N1 and N2. A series-resonant tank circuit formed by an inductance and a capacitance and is energized by the switching action of transistors N1 and N2. A transformer T1 couples energy from the resonance tank circuit to a rectifier bridge BR1 which provides rectified current for charging output capacitor C3. Output voltage V_{OUT} may be maintained at a predetermined voltage during operation by a feedback circuit 12 that provides a feedback signal to switching control circuit 10. Alternatively, operation may be open-loop with respect to output voltage V_{OUT}, which is an especially applicable design if the load impedance across the output is not expected to vary substantially. Switching control circuit 10 may be an integrated circuit integrated on a single die, and may include other elements depicted within the circuit of FIG. 1, for example, switching transistors N1 and N2 and/or feedback circuit 12.

In FIG. 1, the inductance of the resonant tank circuit is illustrated as an inductor L1 plus any leakage inductance of the primary winding of transformer T1. However, it is understood that the inductance of the resonant tank circuit may be entirely supplied by the leakage inductance of transformer T1 and therefore inductor L1 will not be present in some embodiments of the invention. The capacitance of the resonant tank circuit is supplied by the total series capacitance of the tank,

which as illustrated includes the parallel combination of capacitors C1 and C2, the parasitic winding capacitance C_T in parallel with any reflected capacitance at the primary winding of transformer T1, and when neither transistor N1 nor N2 is active, the parallel combination of the parasitic capacitances (C_{pN1}, and C_{pN2}) of transistors N1 and N2.

Switching control circuit 10 adaptively controls a dead-time between the pulses that are generated by turning on transistors N1 and N2, which are activated in alternation to provide alternating pulses of opposite polarity, sourced by one of corresponding power supply voltages $+V_{IN}$ or $-V_{IN}$ to the resonant tank circuit formed by inductor L1 and capacitors C1-C2. If dead-time is not provided between the pulses, when one of transistors N1 and N2 is activated, the charge on the corresponding one of parasitic capacitances C_{pN1} and C_{pN2} would be discharged. Similarly, the other one of parasitic capacitances C_{pN1} and C_{pN2} would be suddenly charged to approximately the full input voltage. The charge placed on and removed from parasitic capacitances C_{pN1} and C_{pN2} when dead-time is not provided represents wasted energy and reduces the efficiency of the resonant converter. Further, the high levels of current required to charge and discharge parasitic capacitances C_{pN1} and C_{pN2} raises stress levels in transistors N1 and N2 and can cause EMI and/or audible noise. By providing a dead-time such that voltage V_S swings to a voltage near the opposite power supply rail after a pulse has terminated, when the next pulse occurs and activates one of transistors N1 or N2, the voltage discharged from the corresponding parasitic capacitor will be much smaller, raising the efficiency of the resonant power converter. Such operation is generally known as zero-voltage switching (ZVS), and as mentioned above, the dead-time is generally set to provide ZVS operation near the highest frequency of operation of the resonant switching power converter, as losses are larger at the higher frequency. (A greater number of transitions occur per unit time interval, and therefore, a greater waste of energy occurs.)

In the present invention, the dead-time between pulses is adaptively controlled. In particular, in digital implementations of a resonant power converter in accordance with an embodiment of the present invention, the timing of pulses is generally determined by counters, and any dead-time provided is also generated from a count value and is set in conformity with a value of the input voltage and an indication of the magnitude of the inductor current I_L flowing through inductor L1, so that an appropriate dead-time is maintained to provide ZVS operation, or alternatively, operation in which the voltage remaining on the parasitic capacitance of the transistor being activated is substantially reduced from the full power supply voltage range.

The indication of the magnitude of inductor current I_L can be obtained from a number of sources, including a measurement circuit that directly measures the inductor current, an example of which is provided by capacitor C_S and resistor R_S in the depicted embodiment. Since the return current at the node connecting transformer T1 to capacitor C_S is split between capacitors C1, C2 and C_S, if a relatively small value of capacitance is used for capacitor C_S, a small portion of inductor current I_L will be passed through capacitor C_S and generate a voltage drop proportional to inductor current I_L across resistor R_S. The voltage across resistor R_S can then be used as a direct indication αI_L of inductor current I_L without significantly affecting the performance of resonant switching power converter. Resistor R_S can be incorporated within an integrated circuit that includes switching control circuit 10 and be internally connected to power supply voltage $-V_{IN}$. In such an implementation, capacitor C_S is connected to a pin of

the integrated circuit, which thereby directly receives the portion of inductor current I_L that passes through capacitor C_S and that serves as an indication of the magnitude inductor current I_L.

In addition to, or as an alternative to, the inductor current measurements described above, the indication of the magnitude of inductor current I_L may be the frequency of operation of the resonant converter, since inductor current I_L is generally proportional to the frequency of operation. For digitally-controlled converters, the frequency of operation is generally already specified in some digital form within switching control 10, since a divider or other mechanism is used to generate the switching frequency that will ultimately generate control signals CA and CB, which control the gate terminals of transistors N1 and N2. Also, in current mode resonant converters, an indication of the output current magnitude is provided from feedback circuit 12 and used to control the switching frequency of the resonant switching power converter and is therefore also proportional to inductor current I_L. In voltage mode resonant converters, a current load current sensing circuit may be included for providing the indication of magnitude of the inductor current, and may be present for other purposes, such as over-current protection. Finally, the inductor current could be sensed directly with a series sense resistor, or a secondary inductor winding provided to a circuit that integrates the voltage across the inductor winding, such as an analog low-pass filter.

Since the frequency of operation is adjusted with line and load conditions in order to maintain a particular output voltage or current level, the line voltage is also generally known in some form at switching control 10. Therefore, using frequency and voltage information available within switching control, the dead-time can be set to different values that provide ZVS operation over the full range of frequencies and load/line conditions at which the resonant switching power converter of FIG. 1 operates.

Referring now to FIG. 2A, an adaptive dead-time control circuit that may be used within switching control 10 of FIG. 1 is shown, in accordance with an embodiment of the invention. A computation block 20A receives at least an input voltage value V_I and some indication of the magnitude of the current flowing through inductor L1, which may be switching frequency F_S, inductor current indication αI_L as measured, or both. Computation block 20A computes an output value Dead Time Count from the input values, which is then used to set a dead time counter 22 that determines the time between the trailing edge of a last pulse and the leading edge of the next pulse. Computation block 20A may be a processing element that computes output value Dead Time Count from input voltage value V_I and the indication of inductor current provided by frequency F_S and/or inductor current indication αI_L, or a dedicated digital circuit may be provided as computation block 20A.

Referring now to FIG. 2B, an adaptive dead-time control circuit that may be used within switching control 10 of FIG. 1 is shown, in accordance with another embodiment of the invention. A look-up table 20B is addressed by at least an input voltage value V_I and some indication of the magnitude of the current flowing through inductor L1, which may be switching frequency F_S, inductor current indication αI_L as measured, or both. Look-up table 20B provides an output value Dead Time Count as selected by the input values, which is then used to set dead time counter 22.

Referring now to FIG. 3, operation of the resonant switching power converter of FIG. 1 is illustrated. Between the active (high) states of control signals CA and CB, a variable dead-time t_d is provided, as determined in conformity with

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input voltage V_I and the indication of inductor current magnitude. Voltage V_S transitions during the dead-times, to voltage V_{ZL} or voltage V_{ZH}, depending on the polarity of inductor current I_L. (When no switching transistor is active, inductor current I_L discharges the capacitance across the transistor that was previously charging the inductor, as can be observed in the continued trend of inductor current I_L during the dead-time.) Voltage V_{ZL} or voltage V_{ZH} are shown apart from the power supply rails for clarity of illustration, and as illustrated at approximately 25% of the power supply rail, can result in efficiency improvement on the order of 16:1 with respect to the energy wasted in charging and discharging parasitic capacitances C_{pN1} and C_{pN2}. However, the voltage at the end of the dead time can be set to exactly a zero voltage difference from the next power supply rail that will be applied to the resonant tank, so that no discharging of parasitic capacitances C_{pN1} and C_{pN2} occurs at all. Further, because voltage V_S will not exceed the power supply rails during the dead-time, but reverses direction at some point due to a start of oscillation in the resonant tank, the dead time can be set by the control circuit to a point anywhere in the vicinity of, either before or after, the reversal of voltage V_S due to the start of oscillation.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made therein without departing from the spirit and scope of the invention.

What is claimed is:

1. A resonant switching power circuit, comprising:
a resonant circuit including at least one inductance and at least one capacitance for transferring energy to an output of the resonant switching power circuit;
a switching circuit coupled to the resonant circuit for transferring energy from an input voltage source to the resonant circuit, wherein the switching circuit includes a first transistor for selectively coupling the resonant circuit to an output node of the input voltage source and a second transistor for selectively coupling the resonant circuit to a return node of the input voltage source; and
a control circuit for controlling the switching circuit such that a dead time between de-activation of one of the first transistor or the second transistor and activation of a second one of the first transistor or the second transistor is dynamically set in dependence on an indication of a magnitude of a current flowing through the inductance and a value of a voltage of the input voltage source.

2. The resonant switching power circuit of claim 1, wherein the indication of the magnitude of the current flowing through the inductance is a switching frequency at which the switching circuit is operated.

3. The resonant switching power circuit of claim 1, further comprising a current measurement circuit for measuring the current flowing through the inductance and wherein the indication of the magnitude of the current flowing through the inductance is obtained from an output of the current measurement circuit.

4. The resonant switching power circuit of claim 3, wherein the current measurement circuit comprises:
a sensing capacitor coupled in parallel with a capacitance of the resonant tank circuit; and
a sensing resistor coupled in series with the sensing capacitor, whereby a voltage drop across the sensing resistor provides the indication of the magnitude of the inductor current.

5. The resonant switching power circuit of claim 1, wherein the indication of the magnitude of the current flowing through

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the inductance is a load current measured at the output of the resonant switching power circuit.

6. The resonant switching power circuit of claim 1, wherein the control circuit comprises a look-up table from which a dead time value is retrieved in conformity with the indication of the magnitude of the current flowing through the inductance and the value of the voltage of the input voltage source, and wherein the control circuit controls the switching times of the first and second transistor in conformity with the dead time value.

7. The resonant switching power circuit of claim 1, wherein the control circuit comprises a circuit that computes a dead time value in conformity with the indication of the magnitude of the current flowing through the inductance and the value of the voltage of the input voltage source, and wherein the control circuit controls the switching times of the first and second transistor in conformity with the dead time value.

8. A method of controlling switching in a resonant switching power circuit, the method comprising:
transferring energy to an output of the resonant switching power circuit from a resonant tank circuit;
transferring energy from an input voltage source to the resonant circuit by operating a switching circuit; and
controlling a dead-time between pulses of the switching circuit in conformity with a voltage of the input voltage source and an indication of a magnitude of a current flowing through an inductance of the resonant tank circuit.

9. The method of claim 8, wherein the indication of the magnitude of the current flowing through the inductance is a switching frequency at which the switching circuit is operated.

10. The method of claim 8, further comprising measuring a current flowing through the inductance and wherein the indication of the magnitude of the current flowing through the inductance is obtained from a result of the measuring.

11. The method of claim 10, wherein the measuring comprises:
passing a portion of the current flowing through a capacitance of the resonant tank circuit through a sensing capacitor; and
measuring a voltage drop across a sensing resistor coupled in series with the sensing capacitor to provide the indication of the magnitude of the inductor current.

12. The method of claim 8, further comprising measuring a value of a load current at the output of the resonant switching power circuit, wherein the indication of the magnitude of the current flowing through the inductance is determined from the value of the load current.

13. The method of claim 8, wherein the controlling the dead-time comprises retrieving a dead-time value from a look-up table in conformity with the indication of the magnitude of the current flowing through the inductance and the value of the voltage of the input voltage source, and wherein the controlling sets the dead-time between the pulses in conformity with the dead time value.

14. The method of claim 8, further comprising computing a dead time value in conformity with the indication of the magnitude of the current flowing through the inductance and the value of the voltage of the input voltage source, and wherein the controlling sets the dead-time between the pulses in conformity with the dead time value.

15. An integrated circuit controller, integrated on a single die, for controlling a resonant switching power converter, wherein the integrated circuit controller provides control signals to a switching circuit that generates pulses provided to an input of a resonant tank circuit that transfers power to a load

from an input voltage source, and wherein the controller includes a control circuit for controlling a dead-time between the pulses in conformity with a voltage of the input voltage source and an indication of a magnitude of a current flowing through an inductance of the resonant tank circuit.

16. The integrated circuit controller of claim **15**, wherein the indication of the magnitude of the current flowing through the inductance is a switching frequency at which the switching circuit is operated.

17. The integrated circuit controller of claim **15**, further comprising an input for receiving a voltage or current indicative of the current flowing through the inductance and wherein the indication of the magnitude of the current flowing through the inductance is obtained from the input.

18. The integrated circuit controller of claim **15**, further comprising an input for receiving a voltage or current indicative of a load current provided to the load, and wherein the

indication of the magnitude of the current flowing through the inductance is obtained from the input.

19. The integrated circuit controller of claim **15**, wherein the control circuit comprises a look-up table from which a dead time value is retrieved in conformity with the indication of the magnitude of the current flowing through the inductance and the value of the voltage of the input voltage source, and wherein the control circuit controls the switching times of the first and second transistor in conformity with the dead time value.

20. The integrated circuit controller of claim **15**, wherein the control circuit comprises a circuit that computes a dead time value in conformity with the indication of the magnitude of the current flowing through the inductance and the value of the voltage of the input voltage source, and wherein the control circuit controls the switching times of the first and second transistor in conformity with the dead time value.

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