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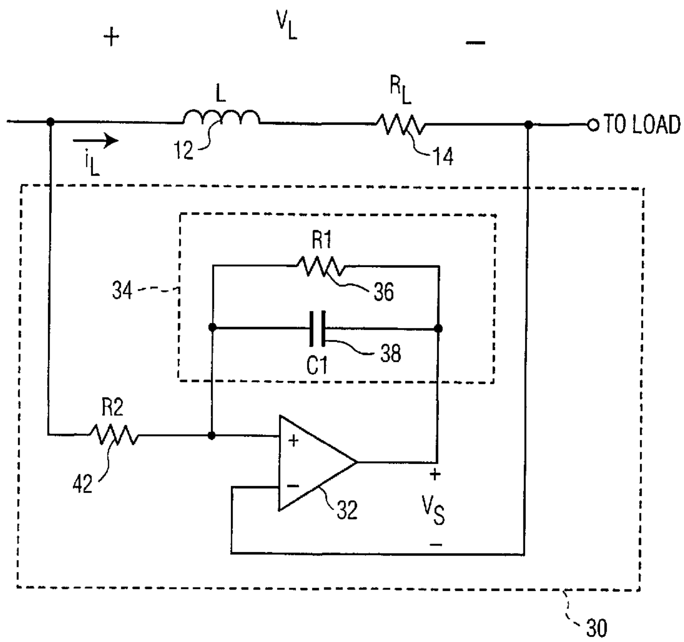
(54) **Title:** METHOD AND APPARATUS FOR NEAR LOSSLESSLY MEASURING INDUCTOR CURRENT



(57) **Abstract:** The present invention provides a measuring circuit for measuring a current of an inductor with minimum losses and errors. According to one embodiment of the invention, the measuring circuit comprises an op-amp (32), a RC network (34) connected in a feedback loop of the op-amp, and a scaling resistor (42) connected in series to one of the input terminals of the op-amp. By setting the RC constant of the RC network to be equal to the ratio of the inductor value over its internal resistance value, the inductor current can be derived independent of the frequencies of AC signals.

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Method and apparatus for near losslessly measuring inductor current

BACKGROUND OF THE INVENTION

The invention generally relates to electronic circuits, and more particularly to methods and apparatuses for near losslessly measuring inductor current.

In switching regulators and particularly multi-phase and other advanced power converters, current through inductors must be accurately measured in order for the control circuitry to timely provide control signals for controlling the operation of the devices. A typical conventional way to measure inductor current is illustrated in FIG. 1.

As shown in FIG. 1, a sampling resistor 10 is connected in series with an inductor 12 and its internal resistance 14. The voltage Vo across sampling resistor 10 is measured by an op-amp 16. From this voltage Vo and the resistance value Rs of sampling resistor 10, the inductor current i_L can be derived to be Vo/Rs. This method, however, suffers from significant losses due to the additional power consumed by sampling resistor 10, which in turn causes inefficiency in the circuit performance.

Another conventional way to measure inductor current is illustrated in FIG. 2. As shown in FIG. 2, a RC network 20 composed of a resistor 22 and a capacitor 24 is used to measure the inductor current i_L. In this method, the voltage across capacitor 24, Vc, is measured. This voltage Vc is taken as the voltage across the inductor 12, from which the inductor current i_L is derived from the expression Vc / Rs. This approach, however, generates significant errors because the load resistance is not taken into account. Practically, this is never the case.

Therefore, there is a need for an improved way of measuring inductor current with minimum losses and errors.

SUMMARY OF THE INVENTION

The present invention provides an improved measuring circuit for measuring a current of an inductor with minimum losses and errors. According to one embodiment of the invention, the measuring circuit comprises an op-amp having first and second input terminals and an output terminal, with the second terminal for connecting a first end of the inductor; a RC network connected between the first input terminal and the output terminal of the op-amp; and a scaling resistor having a first end connected to the first input terminal of the op-amp and a second end for connecting to a second end of the inductor. In a specific embodiment, the RC network comprises a resistor and a capacitor connected to each other in parallel. According to the invention, by setting the RC constant of the RC network to be equal to the ratio of the inductor value over its internal resistance value, the inductor current can be derived independent of the frequencies of AC signals.

Other objects and attainments together with a fuller understanding of the invention will become apparent and appreciated by referring to the following description and claims taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is explained in further detail, and by way of example, with reference to the accompanying drawings wherein:

FIG. 1 illustrates a typical conventional way to measure inductor current;

FIG. 2 illustrates another conventional way to measure inductor current;

FIG. 3 shows a measuring circuit according to a first embodiment of the invention;

FIG. 4 shows a measuring circuit according to second embodiment of the invention; and

FIG. 5 illustrates an application of the second embodiment of the invention in a buck converter.

Throughout the drawings, the same reference numerals indicate similar or corresponding features or functions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 3 shows a current measuring circuit 30 according to a first embodiment of the invention. Circuit 30 includes an op-amp 32, a RC network 34 comprising a resistor 36 and a capacitor 38, and a resistor 42. RC network 34 is connected in a feedback loop of op-amp 32. Resistor 42 is a scaling resistor used for selecting the appropriate gain of circuit 30.

To measure the inductor current i_L, the inductor voltage V_L across inductor L and its internal resistor R_L are first determined. In a DC mode, the voltage V_L can be derived from $V_S/V_L = R1/R2$, where $V_L = i_L \cdot R_L$. Thus, $i_L = V_S \cdot R2/(R1 \cdot R_L)$.

In an AC mode, the inductor voltage can be derived from $V_s/V_L = Z1/R2$, where $Z1 = R1/(1 + j\,\omega\,R1 \cdot C1)$ is the total impedance of the RC network 34. In rewriting the expression $V_s / V_L = Z1 / R2$, the following equation is obtained:

$$V_L / R2 = V_s / Z1$$

where $V_L = i_L\,(j\,\omega\,L + R_L) = i_L\,(j\,\omega\,L + R_L) \cdot R_L/R_L = i_L \cdot R_L\,(1 + j\,\omega\,L / R_L)$,

Thus,

$$i_L \cdot R_L\,(1 + j\,\omega\,L / R_L)/R2 = V_s / (R1 / (1 + j\,\omega\,R1 \cdot C1))$$

or,

$$i_L \cdot R_L\,(1 + j\,\omega\,L / R_L) / R2 = V_s\,(1 + j\,\omega\,R1 \cdot C1) / R1$$

In the above expression, if $R1 \cdot C1$ is chosen to be equal to L / R_L, then

$$i_L \cdot R_L / R2 = V_s / R1$$

or,

$$i_L = V_s \cdot R2 / (R1 \cdot R_L).$$

This expression is true for both DC and AC modes. Thus, i_L can be obtained with this expression, independent of any frequencies of the AC signals. With the present invention, the inductor current i_L can be accurately measured with minimum losses since no additional resistor is used in series with the inductor.

FIG. 4 shows a current measuring circuit 50 according to a second embodiment of the invention. This embodiment is suitable for measuring the current of an inductor which has neither terminal grounded. In this embodiment, a buffer circuit 51 with a unity gain is added to the first embodiment in FIG. 3. Buffer circuit 51 includes an op-amp 52 and four resistors 54-57 of the same resistance value R3. Buffer circuit 51 provides an output voltage Vs' with a ground reference, which is equivalent to the output voltage Vs of op-amp 32. The ground reference is required in many applications.

FIG. 5 illustrates an application of current measuring circuit 50 of the second embodiment of the invention in a buck converter 60. As illustrated in FIG. 5, a controller 62 controls, via transistors 62 and 64, the charging and discharging phases of converter 60, based on the value of the inductor current as measured by measuring circuit 50. The invention may also be used in a converter with a boost topology.

While the invention has been described in conjunction with specific embodiments, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art in light of the foregoing description. Accordingly, it is intended to embrace all such alternatives, modifications and variations as fall within the spirit and scope of the appended claims.

CLAIMS:

1. A measuring circuit for measuring a current of an inductor having an internal resistance, the inductor having a first end and a second end, the circuit comprising:

an op-amp having first and second input terminals and an output terminal, with the second terminal for connecting the first end of the inductor;

a RC network connected between the first input terminal and the output terminal of the op-amp; and

a scaling resistor having a first end connected to the first input terminal of the op-amp and a second end for connecting to the second end of the inductor.

2. The circuit of claim 1, wherein the RC network comprises a resistor and a capacitor connected to each other in parallel.

3. The circuit of claim 2, further comprising a buffer circuit operably coupled to the op-amp for providing an output voltage with a ground reference, which is equivalent to the voltage at the output terminal of the op-amp.

4. The circuit of claim 2, wherein a product of the values of the resistor and capacitor of the RC network is equal to a ratio of the inductor value over the internal resistance value of the inductor.

5. The circuit of claim 4, wherein in both DC and AC modes of operation the inductor current is derived from the following expression:

$$i_L = V_S \cdot R2 / (R1 \cdot R_L)$$

wherein i_L is the inductor current, Vs is a voltage at the output terminal of the op-amp, R1 is the value of the resistor in the RC network, R2 is the value of the scaling resistor, and R_L is the internal resistance of the inductor.

6. The circuit of claim 5, wherein the first and second terminals of the op-amp are respectively positive and negative terminals of the op-amp.

7. A measuring circuit for measuring a current of an inductor having an internal resistance, the inductor having a first end and a second end, the circuit comprising:

op-amp means having first and second input terminals and an output terminal, with the second terminal for connecting the first end of the inductor;

RC network means connected between the first input terminal and the output terminal of the op-amp; and

scaling resistor means having a first end connected to the first input terminal of the op-amp and a second end for connecting to the second end of the inductor.

8. The circuit of claim 7, wherein the RC network means comprises a resistor and a capacitor connected to each other in parallel.

9. The circuit of claim 8, wherein a product of the values of the resistor and capacitor of the RC network means is equal to a ratio of the inductor value over the internal resistance value of the inductor.

10. The circuit of claim 9, wherein in both DC and AC modes of operation the inductor current is derived from the following expression:

$$i_L = Vs \cdot R2 / (R1 \cdot R_L)$$

wherein i_L is the inductor current, Vs is a voltage at the output terminal of the op-amp means, R1 is the value of the resistor in the RC network means, R2 is the value of the scaling resistor means, and R_L is the internal resistance of the inductor.

11. The circuit of claim 10, wherein the first and second terminals of the op-amp means are respectively positive and negative terminals of the op-amp means.

12. A converter, comprising:

an input circuit for receiving input signals;

an output circuit including an inductor having an internal resistance, the inductor having a first end and a second end;

a control circuit for controlling the input circuit based on a current of the inductor; and a measuring circuit for measuring the inductor current, the measuring circuit including:

an op-amp having first and second input terminals and an output terminal, with the second terminal for connecting the first end of the inductor,

a RC network connected between the first input terminal and the output terminal of the op-amp, and

a scaling resistor having a first end connected to the first input terminal of the op-amp and a second end for connecting to the second end of the inductor.

13. The converter of claim 12, wherein the RC network comprises a resistor and a capacitor connected to each other in parallel.

14. The converter of claim 13, wherein a product of the values of the resistor and capacitor of the RC network is equal to a ratio of the inductor value over the internal resistance value of the inductor.

15. The converter of claim 14, wherein in both DC and AC modes of operation the inductor current is derived from the following expression:

$$i_L = Vs \cdot R2 / (R1 \cdot R_L)$$

wherein i_L is the inductor current, Vs is a voltage at the output terminal of the op-amp, R1 is the value of the resistor in the RC network, R2 is the value of the scaling resistor, and R_L is the internal resistance of the inductor.

16. The converter of claim 15, wherein the measuring circuit further comprises a buffer circuit operably coupled to the op-amp for providing an output voltage with a ground reference, which is equivalent to the voltage at the output terminal of the op-amp.

17. A method for measuring a current of an inductor having an internal resistance, the inductor having a first end and a second end, the method comprising:

connecting a RC network between a first input terminal and an output terminal of an op-amp;

connecting the output terminal of the op-amp to the first end of the inductor; and connecting a first end of a scaling resistor to the first input terminal of the op-amp and a second end of the scaling resistor to the second end of the inductor.

18. The method of claim 17, wherein the RC network comprises a resistor and a capacitor connected to each other in parallel.

19. The method of claim 18, wherein a product of the values of the resistor and capacitor of the RC network is equal to a ratio of the inductor value over the internal resistance value of the inductor.

20. The method of claim 19, further comprising, in both DC and AC modes of operation, deriving the inductor current from the following expression:

$$i_L = Vs \cdot R2 / (R1 \cdot R_L)$$

wherein i_L is the inductor current, Vs is a voltage at the output terminal of the op-amp, R1 is the value of the resistor in the RC network, R2 is the value of the scaling resistor, and R_L is the internal resistance of the inductor.

21. A computer system, comprising:

a memory;

a processor connected to the memory; and

a converter connected to the processor for converting a first voltage level to a second voltage level, the converter including:

an input circuit for receiving input signals,

an output circuit including an inductor having an internal resistance, the inductor having a first end and a second end,

a control circuit for controlling the input circuit based on a current of the inductor, and

a measuring circuit for measuring the inductor current, the measuring circuit including:

an op-amp having first and second input terminals and an output terminal, with the second terminal for connecting the first end of the inductor;

a RC network connected between the first input terminal and the output terminal of the op-amp, the RC network comprising a resistor and a capacitor connected to each other in parallel; and a scaling resistor having a first end connected to the first input terminal of the op-amp and a second end for connecting to the second end of the inductor;

wherein a product of the values of the resistor and capacitor of the RC network is equal to a ratio of the inductor value over the internal resistance value of the inductor.

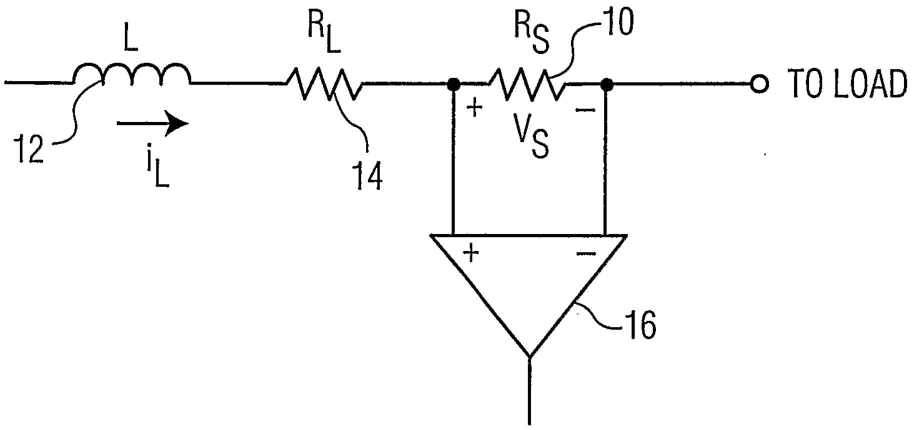

FIG. 1

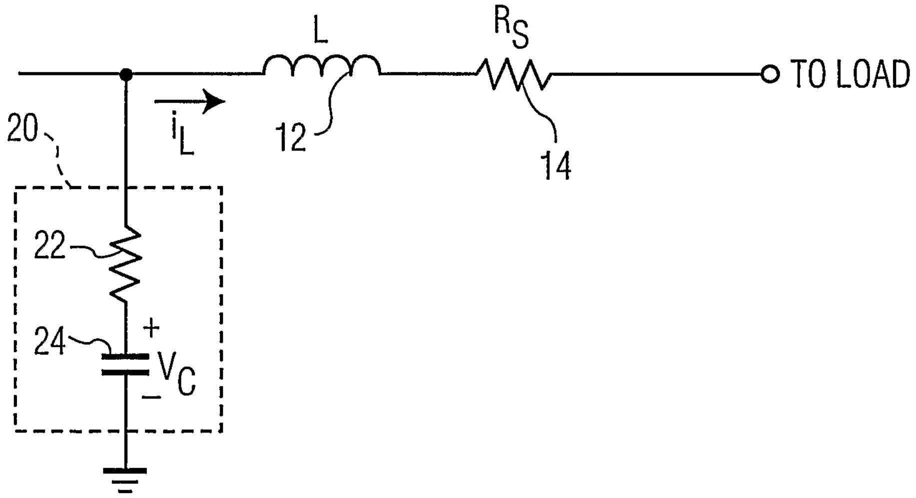

FIG. 2

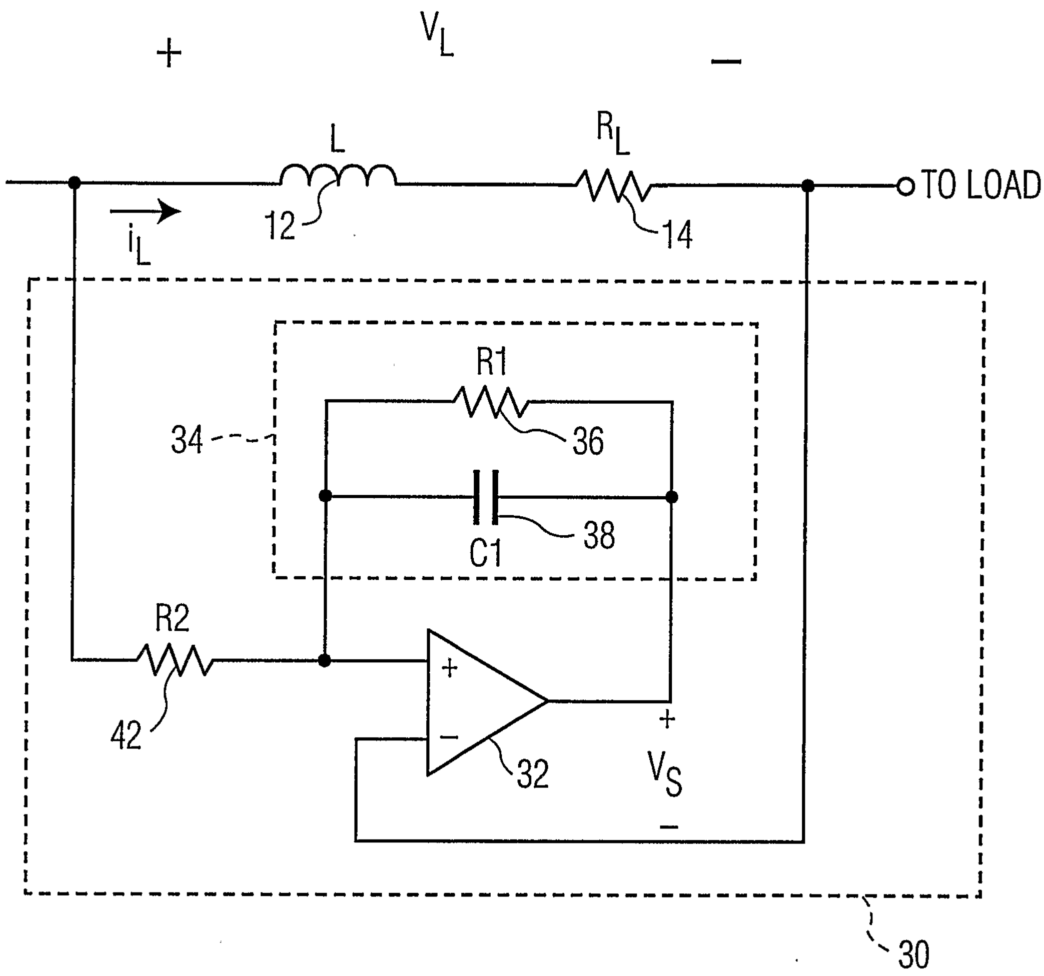

FIG. 3

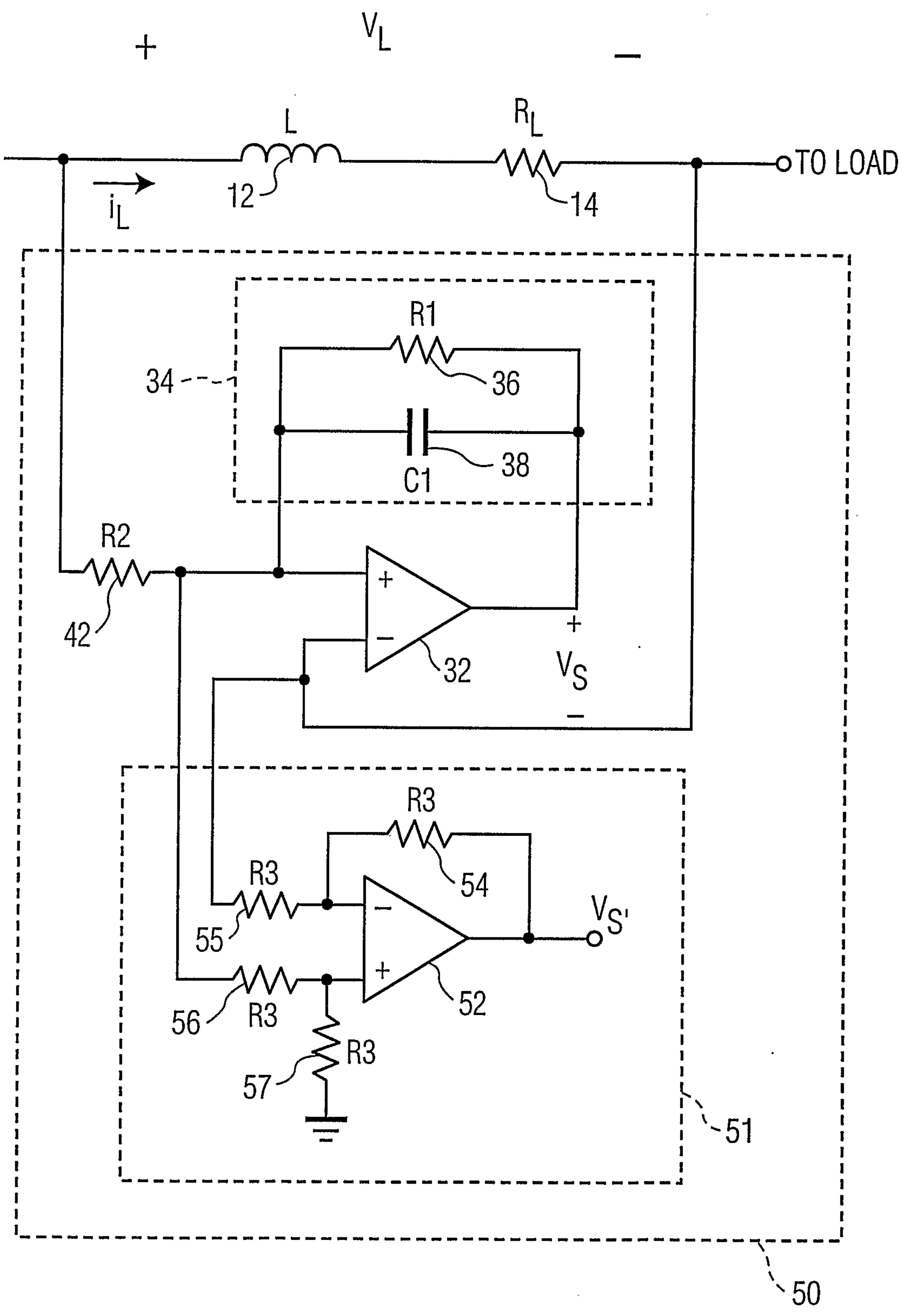
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FIG. 4

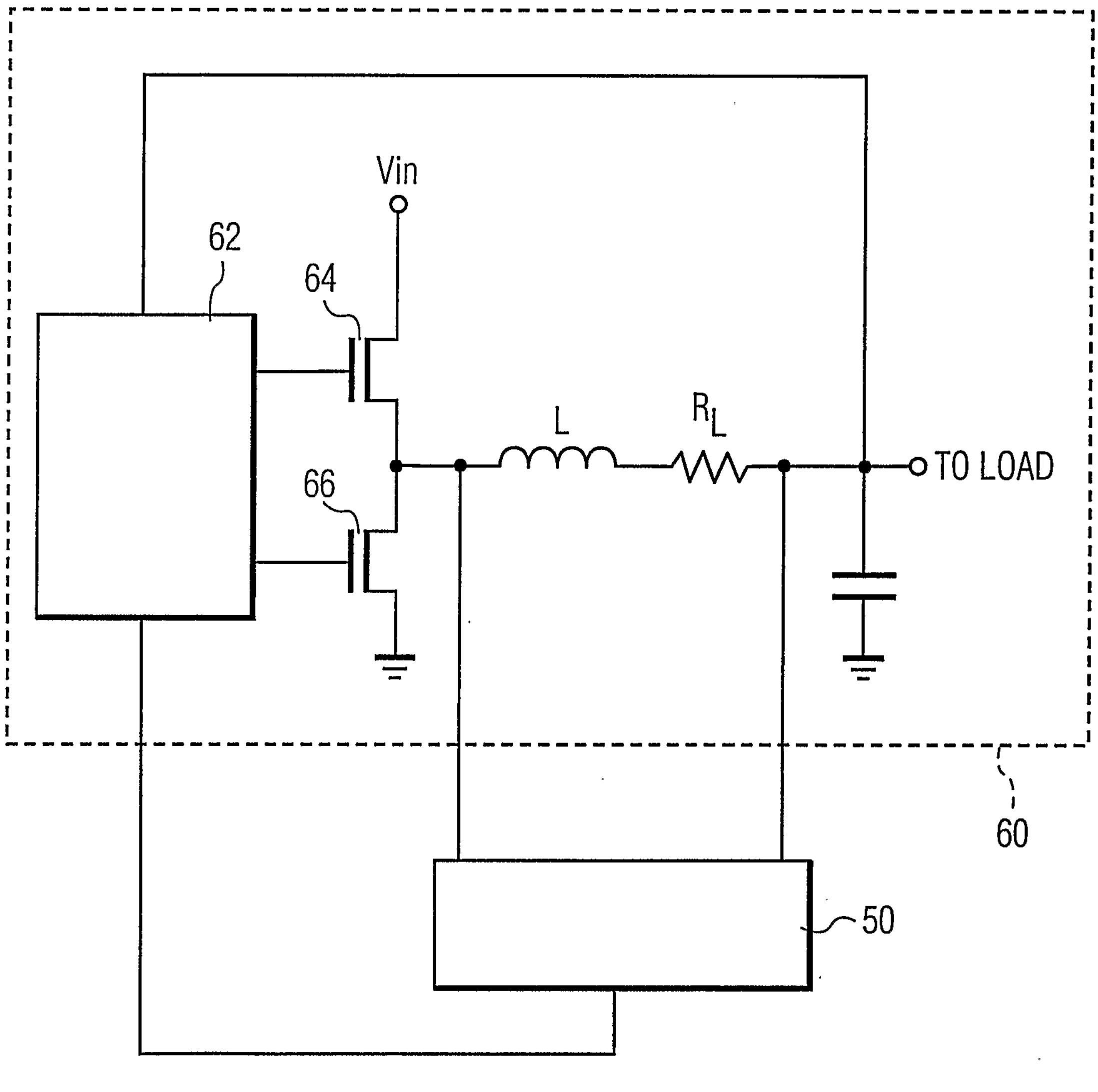

FIG. 5

INTERNATIONAL SEARCH REPORT

Int ional Application No
PCT/IB 02/03902

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H02M3/156 G01R19/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H02M G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 473 428 A (WESTINGHOUSE ELECTRIC CORP) 4 March 1992 (1992-03-04) column 3, line 8 - line 37; figure 2	1-3,7,8, 12,13, 17,18
X	WO 99 57578 A (AIRPAX CORP L L C ;GOODWIN SHAUN (US); KUSTERA DANIEL (US)) 11 November 1999 (1999-11-11) abstract; figure 11	1,2,7,8, 17,18
A	EP 1 109 303 A (TEXAS INSTRUMENTS INC) 20 June 2001 (2001-06-20) abstract; figure 1	21
A	US 6 222 356 B1 (TAGHIZADEH-KASCHANI KARIM-THOM) 24 April 2001 (2001-04-24) abstract; figure 1	1,7,12, 17,21

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
5 December 2002	16/12/2002

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 02/03902

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