Voltage regulators often have coupled output inductors because coupled output inductors provide improvements in cost and efficiency. Coupled inductors are often used in multi-phase voltage regulators. Feedback control of voltage regulators often requires accurate and responsive sensing of output current. Provided is a technique for accurately sensing the magnitude of output current in coupled inductors. An RC circuit (comprising a resistor and capacitor in series) is connected in parallel with the coupled inductor. The inductor has a leakage inductance $L_k$ and a DC ohmic resistance of $\text{DCR}$. The resistor and capacitor are selected such that an RC time constant is equal to an $L/R$ time constant of $L_k/\text{DCR}$. With the matching time constants, a sum of voltages on the capacitors is accurately proportional to a sum of currents flowing in the output inductors. Also provided is a technique for sensing current when an uncoupled center tap inductor is present.
Fig. 3

Fig. 4

Magnetic Core 20

Air Gap

Q1, Q2

Co

Q3, Q4

Phase 1

Phase 2

Phase 3

L1

L2

Rc1

Capacitor

Source

Current Sense Voltage

DCR1

26a

26b

20a

20b

20c

Capacitor or voltages from phases 2 & 3

DCR2

28a

28b

28c

DCR3

27a

27b

Q1, Q2

Q3, Q4

Q5, Q6
Fig. 5
CURRENT SENSING IN MULTIPLE COUPLED INDUCTORS BY TIME CONSTANT MATCHING TO LEAKAGE INDUCTANCE

FIELD OF THE INVENTION

The present invention relates generally to sensing electrical current flowing through coupled inductors. More specifically, it relates to a DC resistance (DCR) technique for sensing current flowing through coupled output inductors in a voltage regulator or DC to DC converter.

BACKGROUND OF THE INVENTION

Voltage regulators (VRs) and DC-to-DC converters are widely used for providing electrical power for computer processors and telecommunications electronics. Many voltage regulators include circuits for measuring output current and voltage so that feedback control of the voltage regulator is possible. One method for feedback control is adaptive voltage positioning (AVP), in which the output voltage is controlled in response to the output current. AVP is particularly well suited for use in microprocessor voltage regulators and voltage regulators for memory and graphics-processing circuits. AVP typically requires accurate and high speed sensing of output current.

One method for accurate and high speed output current sensing is known as direct current resistance (DCR) sensing. DCR sensing is described in U.S. Pat. No. 5,982,160. FIG. 1 illustrates a buck regulator circuit employing DCR current sensing. The voltage regulator can also have a third output inductor. The voltage regulator can be a multiple phase buck regulator or other multiple phase voltage regulator. The regulator can have 3, 4, 5, 6, 7, 8 or more phases, for example.

The voltage regulator can also have a third output inductor and a third RC circuit, or any other number of coupled inductors and RC circuits. The present invention includes a voltage regulator having first and second output inductors. The inductors are magnetically coupled (e.g. by a ferrite core). The first output inductor has a leakage inductance Lk1 and DC (ohmic) resistance of DCR1. An RC circuit is connected in parallel with the first output inductor. The RC circuit comprises a resistor and capacitor connected in series. The RC circuit has an RC time constant equal to Lk1/DCR1. In other words, the RC circuit and first output inductor have matching time constants, based on the leakage inductance (not the total inductance or self-inductance) of the first inductor. When the RC circuit and inductor are matched in this way, a voltage across the capacitor of the RC circuit is roughly representative of a current flowing through the first inductor. It is noted that the voltage on the capacitor is not accurately proportional to the current flowing through the first inductor. A second RC circuit can be connected in parallel with the second output inductor. Also a voltage adder can be provided for receiving and adding voltages present on the capacitors of the RC circuits. The voltage adder will in this case output a voltage that is accurately proportional to a sum of currents flowing through the first and second output inductors. The output of the voltage adder will be accurately proportional to a total current flowing in the output inductors provided that every coupled inductor has a corresponding RC circuit providing a signal to the voltage adder.

The voltage regulator can be a multiple phase buck regulator or other multiple phase voltage regulator. The regulator can have 3, 4, 5, 6, 7, 8 or more phases, for example.

The voltage regulator can also have a third output inductor and a third RC circuit, or any other number of coupled inductors and RC circuits. The RC time constants of the RC circuits can match the LR time constants (Lk1/DCR1) of the output inductors to within 20%, 10%, or 5%, for example.

Preferably, all the coupled inductors have the same values or leakage inductance (Lk) and DC resistance (DCR).

Also, voltage buffers or amplifiers can be connected to the capacitors. Voltage buffers or amplifiers will improve the accuracy of the current sensing circuit by preventing current drain from the capacitors.
Also, the present invention includes an embodiment for sensing current flowing through coupled inductors when a center tap inductor is provided. In this embodiment, the voltage regulator has N phases (where N ≥ 2). The voltage regulator has at least two coupled output inductors, with each of the coupled output inductors in different phases of the voltage regulator. A center tap inductor receives electrical current from all the coupled output inductors and is connected in series with the coupled output inductors. The center tap inductor is not magnetically coupled to the coupled output inductors. The center tap inductor has an inductance Lko and a DC resistance DCRo. An RC circuit (comprising a resistor and a capacitor connected in series) is connected in parallel with at least one of the coupled output inductors and the center tap inductor. The coupled inductor connected in parallel with the RC circuit has a DC resistance DCR. In the present invention, the RC circuit has an RC time constant equal to

\[
\frac{L_{ko}}{(DCR_o + DCR/N)}
\]

With the RC time constant selected in this way, a voltage on the capacitor will be roughly representative of current flowing through the output inductor connected in parallel with the RC circuit. Hence, the current flowing through the inductor can be monitored by monitoring the voltage on the capacitor. Preferably, voltages from the capacitors are added at a voltage adder. In this case, the voltage output of the voltage adder will be accurately proportional to a total sum of currents flowing through the coupled inductors.

The RC time constant can be matched to the above equation to within 20%, 10%, or 5% for example.

Preferably, the mutual inductance of the coupled inductors is 3–20 times as great as the self-inductance of the center tap inductor. Also preferably, the self-inductance of the center tap inductor is at least 10 times as great as a leakage inductance of each of the coupled inductors. Preferably, in the embodiment having the center tap inductor, the coupled inductors have a very small or negligible leakage inductance.

The voltage regulator can have N RC circuits, with each RC circuit connected in parallel with a coupled inductor and the center tap inductor. In this case, the current flowing through N coupled inductors can be monitored. Also, a voltage adder can be provided for receiving voltages across capacitors of the RC circuits, and producing a voltage that is accurately proportional to a sum of currents flowing through the coupled output inductors.

The voltage regulator can be an N phase buck regulator, with one RC circuit for sensing current in each phase.

**DESCRIPTION OF THE FIGURES**

FIG. 1 (Prior Art) shows a buck regulator with DCR current sensing according to the prior art.

FIG. 2 shows a two-phase buck regulator according to the present invention. The buck regulator has coupled output inductors, and a current sensing circuit according to the present invention.

FIG. 3 shows exemplary coupled output inductors that can be used in the circuit of FIG. 2.

FIG. 4 shows a 3-phase buck regulator according to the present invention.

FIG. 5 shows a 3-phase buck regulator according to the present invention having a single current sensor (comprising RC circuit 22 and voltage buffer 28) for sensing current in phase 1 only.

FIG. 6 shows an alternative embodiment of the present invention in which the two-phase buck regulator has a center tap inductor connected to a center tap of the coupled output inductors.

FIG. 7 shows exemplary coupled output inductors and center tap inductor that can be used in the circuit of FIG. 6.

FIG. 8 shows a full wave bridge voltage regulator that can use the current sensing circuit of the present invention. The present current sensor can be used in any type of voltage regulator having coupled output inductors.

**DETAILED DESCRIPTION**

The present invention provides circuits for accurately sensing current flowing through coupled inductors. The present inventors have discovered that an RC circuit (comprising a resistor and capacitor connected in series) connected across each of two or more coupled inductors can be used to sense a sum of currents through the inductors if the RC time constant is matched to Lk/R, where Lk is the leakage inductance and R is the DC (ohmic) resistance of the inductor. In other words, the mutual inductance of a coupled inductor does not affect the time constant matching required between the inductor and the RC circuit. The present invention allows DCR current sensing techniques to be applied to coupled inductors and multi-phase voltage regulators. The present invention can be used for accurate current sensing in multiple phase voltage regulators, which commonly have coupled inductors.

In the present specification, "leakage inductance" is defined as that portion of an inductors inductance that is not coupled to other inductors. In other words, the leakage inductance is the portion of inductance that is not associated with the mutual inductance.

In the present specification, a "RC circuit" is a circuit having a resistor and a capacitor connected in series.

In the present specification, a "coupled inductor" is an inductor that has a significant mutual inductance with another coupled inductor.

FIG. 2 shows a 2-phase buck regulator according to the present invention. The 2-phase buck regulator has top switches Q1 Q3 and bottom switches Q2 Q4 connected between a power source Vin and ground, as known in the art. A first output inductor L1 and a second output inductor L2 are coupled by a magnetic core 20 (e.g. made of ferrite), and have a mutual inductance (not illustrated). A first RC circuit 22 is connected in parallel with the first output inductor L1. A second RC circuit 24 is connected in parallel with the second output inductor L2. The output inductors L1 L2 are connected to an output capacitor Co and the load 25.

Each output inductor L1 L2 is illustrated as comprising three ideal components in series: a DC resistance DCR1, DCR2, a leakage inductance Lk1 Lk2, and an ideal coupled inductance 26 28. The ideal coupled inductances 26 28 comprise an ideal transformer. The DC resistance is the resistance to DC current. In other words, the DC resistance is the ohmic resistance of the coils of the inductors L1 L2. The leakage inductance Lk1 Lk2 is the inductance that is not coupled between the inductors.

Typically, the leakage inductances Lk1 Lk2 will be smaller than the mutual inductance of the coupled inductors L1 L2. For example, the ratio between the coupled inductances 26 28, and the leakage inductances Lk1 Lk2 will
matched. However, a match within 20%, 10% or 5% is
whereas the current flowing in each phase is not.

It is important to note that the coupled inductors in FIG.
2 comprise a transformer with a relatively high but con-
trolled amount of leakage inductance. FIG. 3, for example,
shows an exemplary coupled inductor (i.e. transformer)
structure that can be employed for the coupled inductors L1
and L2. The output terminal is connected to the output capacitor Co. The structure has a magnetic core 20 with an air gap (or other features) designed to provide a controlled amount of
leakage inductance in the output inductors L1 and L2.

In the present invention, it is essential for the RC circuits
22 24 to be matched to the leakage inductance values of
the coupled inductors L1 L2. The RC circuits are not matched
to the total self-inductance values of the coupled inductors
L1 and L2. Specifically, in the invention, the RC circuits 22
and inductors L1 and L2 are matched such that (Rc1)(C1):Lk1/
DCR1 and (Rc2)(C2):Lk2/DCR2. In other words the RC
time constant is set equal to the RL time constant calculated
from the DC resistance and leakage inductance values. The
present inventors have discovered that when the RC circuits
and coupled inductors are matched in this way, the sum of
voltages across the capacitors C1 C2 is proportional to the
sum of currents flowing through the coupled inductors L1
and L2. The total current flowing through both coupled
inductors L1 and L2 can be determined by adding the voltages
across the capacitors C1 C2. The voltage adder 32 performs
this function and provides a voltage output (the current sense
voltage) that is accurately proportional to the sum of cur-
rents flowing through both output inductors L1 L2.

It is important to note that the voltages on capacitors C1
and C2 is not necessarily accurately representative of the current
flowing through each of the inductors L1 and L2. Hence, in the
present invention, it is generally not possible to accurately
determine the current in each inductor L1 and L2. However, the
present invention does allow the accurate sensing of a sum of
currents in the inductors L1 and L2. For AVP and other
feedback techniques in multi-phase voltage regulators, the
total current (i.e. sum of currents in each phase) is important,
whereas the current flowing in each phase is not.

In the present invention, the RC circuits 22 24 and
inductors L1 L2 do not need to be matched extremely
accurately. The current sensing will be accurate if the RC
circuits and coupled inductors L1 L2 are accurately matched. However, a match within 20%, 10% or 5% is adequate for many applications of the present invention. In

critical applications, a match of better than 1% or 2% may
be required. An accurate match is preferred in the invention.
However, high tolerance electronic components are expen-
sive and present cost-performance accuracy tradeoffs.

The voltage buffers 29 30 are preferred because they
provide more accurate current measurement, but they are not
essential in the invention. Voltage from the capacitors C1 C2
can be provided directly to the voltage adder 32, particularly
if the voltage adder has high impedance inputs.

In operation, the voltages across the capacitors C1 and C2
can be continuously or intermittently monitored by the voltage
buffers 29 30 and continuously or intermittently provided to
the voltage adder 32. The current sense voltage produced by
the voltage adder will be accurately proportional to the sum
of currents flowing through the coupled inductors L1 L2.
The current sense voltage can be used for feedback control
of the voltage regulator, as known in the art. For example,
the current sense voltage can be used for adaptive voltage
positioning (AVP) control of the voltage regulator, for
overload protection, for pulse-width modulation of the
switches Q1 Q2 Q3 Q4 or for other forms of feedback
control known in the art.

It is important to note that the present invention and
appended claims include embodiments having 3, 4, 5, 6, 7,
8 or more phases. Inductors in each phase can be coupled to
inductors in every other phase. FIG. 4, for example, illustrates
a 3-phase buck regulator according to the present
invention. For brevity and clarity, the RC circuits and buffers
for phases 2 and 3 are not illustrated, though they may be
present. In the circuit of FIG. 4, each phase has two coupled
inductors. For example, phase 1 has coupled inductors 26a
and 26b, and phase 2 has coupled inductors 28a and 28b.
The coupled inductors 26a 26b 28a 28b 27a 27b are coupled
to three magnetic cores 20a 20b 20c. (magnetic cores 20a
20b 20c can be discrete magnetic cores, or can be combined
in a single integrated magnetic core). It is important to note
that the DC resistances DCR1 DCR2 DCR3 and leakage
inductances Lk1 Lk2 Lk3 are associated with both the
coupled inductors 26a 26b 28a 28b 27a 27b in each phase.
For example, the DC resistance DCR1 is the sum of the
ohmic resistances associated with coupled inductors 26a
and 26b. Similarly, the leakage inductance Lk1 is the sum of
the leakage inductances associated with coupled inductors
26a and 26b.

Preferably, DC resistances DCR1 DCR2 DCR3 have the
same values (e.g. matched to within 10% or 20% or 30%).
Also preferably, leakage inductances Lk1 Lk2 Lk3 have the
same values (e.g. matched to within 10% or 20% or 30%).

Also, it is noted that in the present invention, it is not
required to have a current sensor (comprising an RC circuit,
and, optionally, a voltage buffer) for every phase. It is within
the scope of the present invention and appended claims to
have only one (or more) RC circuits in a multiphase regu-
lator. In the present invention, it is possible to sense current
(i.e. an average current) in only a single phase of a multi-
phase regulator having coupled inductors. FIG. 5, for
example, shows a 3-phase buck regulator in which only
phase 1 has a current sensor (comprising RC circuit 22
and voltage buffer 28). In this embodiment, the voltage adder 32
is not necessary. It is noted that in embodiments where only
a single phase has a current sensor, the RC circuit and
coupled inductors must be matched in the same way as noted
above. Specifically, the RC circuit and coupled inductor of
phase 1 must be matched such that (Rc1)(C1):Lk1/DCR1.
The coupled inductors 28a 28b 27a 27b, DC resistances
the uncoupled inductor \( L_O \) is illustrated as containing a pure leakage inductance.

However, it is important to note that a single current sensor will provide a rough measurement of the current in the phase to which it is connected. The current measurement will be accurate when averaged over a long period of time (e.g., many cycles), but will generally not be accurate at any particular instant. Accurate current sensing at every instant can only be provided for a total sum of currents for all the phases.

In some cost sensitive applications, it may be desirable to have the current sensor on only a single phase, since the voltage adder \( 32 \) and other components will not be necessary. However, if not every phase has a current sensor, then the current sense voltage might not be accurate and responsive enough to support AVP.

FIG. 7 illustrates an exemplary structure for the coupled inductors \( L_1 \) and \( L_2 \) and uncoupled center tap inductor \( L_O \) in the embodiment of FIG. 6. It is clear that center tap inductor \( L_O \) is not magnetically coupled to \( L_1 \) or \( L_2 \), and therefore behaves as a pure leakage inductance.

In the embodiment of FIG. 6, the RC circuits \( 22, 24 \) must be matched according to the resistances \( DCR_0 \) \( DCR_1 \) \( DCR_2 \) and inductance \( L_{ko} \). The inductance values of coupled inductors \( L_{k1} \) \( L_{k2} \) do not affect the required RC time constant for the RC circuits \( 22, 24 \). Specifically, for the 2 phase embodiment of FIG. 6, the RC circuit \( 22 \) must be matched such that:

\[
R_{c1} C_1 = \frac{L_{ko}}{DCR_0 + \frac{DCR_1}{2}}
\]

Similarly, RC circuit \( 24 \) must be matched such that:

\[
R_{c2} C_2 = \frac{L_{ko}}{DCR_0 + \frac{DCR_2}{2}}
\]

When voltages from the capacitors \( C_1 \) \( C_2 \) are provided to the voltage adder \( 32 \), the output of the voltage adder is accurately proportional to an instantaneous total sum of currents in the inductors \( L_1 \) \( L_2 \). Hence, the present invention allows current sensing in coupled inductors when a center tap inductor \( L_O \) is connected to the coupled inductors. It is important to note that the above equation is based on the assumption \( DCR_1 = DCR_2 \). This will almost always be the case in multiphase voltage regulators because each phase is typically identical.

It is noted that the circuit of FIG. 6 can be expanded to have 3, 4 or more phases, with RC circuits provided for each phase. In this case, the RC circuits must be matched such that:

\[
R_{c} C_n = \frac{L_{ko}}{DCR_0 + \frac{DCR_n}{N}}
\]

where \( N \) is the total number of phases, and \( n \) is a phase number index (e.g. \( n=1 \) for RC circuit \( 22 \), and \( n=2 \) for RC circuit \( 24 \) in the embodiment of FIG. 6). When this matching condition is met, the sum of voltages across the capacitors \( C_2 \) \( C_2 \) \( \ldots \) \( C_n \) will be accurately proportional to the sum of current flowing through the coupled inductors \( L_1 \) \( L_2 \) \( \ldots \) \( L_n \). A voltage adder can be used to add the voltages and provide a sum of all the currents in the coupled inductors.

It is important to note that the above equation requires that \( DCR_1 = DCR_2 = \ldots = DCR_n \). This will almost always be the case in multiphase voltage regulators.

Also, it is important to note that, in the embodiments having a center tap inductor \( L_O \), it is not required for every phase to have an associated RC circuit. For example, a single RC circuit can be provided for measuring the time-averaged current in a single one of the output inductors. Time-averaged current sensing is adequate for providing current sharing among phases in a multi-phase converter, or for other applications. Also for example, 2 or 3 of 4 phases can have an associated RC circuit. Such embodiments are within the scope of the invention and appended claims.

The present invention can be used with many different kinds of voltage regulators for sensing current flowing through coupled inductors. FIG. 8, for example shows a voltage regulator having coupled output inductors \( L_1 \) \( L_2 \). Secondary switches \( S_1 \) \( S_2 \) are operated to rectify the power from transformer \( 40 \). The RC circuits \( 22, 24 \) are connected in parallel with coupled inductors \( L_1 \) \( L_2 \). In FIG. 8 the primary circuit is a full bridge. However, the full bridge primary circuit can be replaced with a symmetric half bridge circuit or a push-pull circuit, for example.

The present invention provides a simple and accurate technique for sensing current in coupled inductors. The present invention can be used in any voltage regulator where it is necessary to sense current in coupled inductors. The present invention can be used in multi-phase buck regulators, multi-phase boost regulators, multi-phase buck-boost regulators, full bridge regulators, and any in multi-phase DC—DC converter or regulator having coupled inductors.

The present invention is particularly well suited for implementing adaptive voltage positioning in microprocessor voltage regulators, memory voltage regulators, and other electronic circuits requiring well-regulated electrical power.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing...
from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

What is claimed is:

1. A voltage regulator, comprising:
   a first output inductor a DC resistance DCR1;
   a second output inductor, arranged magnetically mutually coupled with the first output inductor, wherein the arrangements of the first and second output inductors is such that the first output inductor has a leakage inductance Lk1; and a first RC circuit connected in parallel with the first output inductor, the first RC circuit comprising a resistor and a capacitor connected in series, wherein the first RC circuit is arranged to have an RC time constant approximately equal to Lk1/DCR1.

2. The voltage regulator of claim 1 wherein the first and second output inductors are arranged such that the second output inductor has has a DC resistance DCR2, and wherein the first and second output inductors are arranged such that the second output inductor has a leakage inductance Lk2 and further comprising:
   a second RC circuit connected in parallel with the second output inductor, wherein the second RC circuit comprises a resistor and a capacitor connected in series, and wherein the second RC circuit is arranged to have an RC time constant approximately equal to Lk2/DCR2; and
   a voltage adder for adding voltages across capacitors in the first and second RC circuits, whereby a voltage output of the voltage adder is proportional to a sum of currents flowing through the first and second output inductors.

3. The voltage regulator of claim 1 wherein the voltage regulator is a multiple phase buck regulator and each output inductor is an output inductor of a separate buck regulator phase.

4. The voltage regulator of claim 2 wherein the first RC circuit has an RC time constant equal to Lk1/DCR1 to within 20%, and wherein the second RC circuit has an RC time constant equal to Lk2/DCR2 to within 20%.

5. The voltage regulator of claim 2 wherein the first RC circuit has an RC time constant equal to Lk1/DCR1 to within 10%, and wherein the second RC circuit has an RC time constant equal to Lk2/DCR2 to within 10%.

6. The voltage regulator of claim 2 further comprising a first voltage buffer or amplifier receiving voltage across the capacitor in the first RC circuit, a second voltage buffer or amplifier receiving voltage across the capacitor in the second RC circuit, and each voltage buffer or amplifier providing voltage to the voltage adder.

7. The voltage regulator of claim 2 wherein Lk1=Lk2 to within 10%.

8. The voltage regulator of claim 2 wherein DCR1=DCR2 to within 10%.

9. The voltage regulator of claim 2 further comprising: a third output inductor, arranged magnetically coupled to the first and to the second inductor, having a leakage inductance Lk3 and a DC resistance DCR3; a third RC circuit connected in parallel with the third output inductor,
   wherein the first RC circuit comprises a resistor and a capacitor connected in series, and wherein the third RC circuit has an RC time constant approximately equal to Lk3/DCR3,
   and wherein the voltage adder adds voltages across capacitors in the first, second, and third RC circuits, whereby a voltage output of the voltage adder is proportional to a sum of currents flowing through the first, second, and third output inductors.

10. The voltage regulator of claim 2 wherein Lk1=Lk2=Lk3 to within 10% and DCR1=DCR2=DCR3 to within 10%.

11. A voltage regulator having N phases, where N≥2, comprising:
   a center tap inductor receiving electrical current from and connected in series with each of the coupled output inductors, wherein the center tap inductor is not magnetically coupled to the coupled output inductors, and wherein the center tap inductor has a self inductance Lko and a DC resistance DCRo; and
   an RC circuit connected in parallel with one of the coupled output inductors and the center tap inductor, wherein the RC circuit comprises a resistor and a capacitor connected in series, and wherein the RC circuit has an RC time constant approximately equal to
   \[
   \frac{Lko}{DCRo + \frac{DCR}{N}}.
   \]

12. The voltage regulator of claim 11, wherein the center tap inductor has an inductance at least 10 times as great as a leakage inductance of each of the coupled inductors.

13. The voltage regulator of claim 11, wherein the voltage regulator comprises N RC circuits, and comprises at least one coupled output inductor in each phase, wherein one RC circuit is connected in parallel with an output inductor in each phase and the center tap inductor, and wherein each coupled output inductor has a DC resistance DCRn, where n is a phase index, and wherein each RC circuit has an RC time constant approximately equal to
   \[
   \frac{Lko}{DCRo + \frac{DCR}{N}}.
   \]

and further comprising:
   a voltage adder for adding voltages across capacitors in the N RC circuits, whereby a voltage output of the voltage adder is proportional to a sum of currents flowing through the N output inductors.

14. The voltage regulator of claim 11, wherein the N phase voltage regulator is an N phase buck regulator, and wherein each of the coupled output inductors is an output inductor for a buck regulator phase.

15. The voltage regulator of claim 11, wherein the RC circuit has an RC time constant equal to
   \[
   \frac{Lko}{DCRo + \frac{DCR}{N}}
   \]
   to within 20%.
11. The voltage regulator of claim 11, wherein the RC circuit has an RC time constant equal to
\[
\frac{L_{\text{in}}}{(DCR_1 + \frac{DCR}{N})}
\]
to within 10%.

12. The voltage regulator of claim 13, wherein the voltage regulator comprises N voltage buffers or amplifiers receiving voltages from across capacitors in the N RC circuits, and wherein the voltage adder adds voltages from the N voltage buffers or amplifiers.

13. An N-phase voltage regulator, wherein each phase includes:
(a) a plurality of coupled output inductors, constructed and arranged such that each of the coupled output inductors is coupled to at least one other of the output inductors, a first of said coupled output inductors having a leakage inductance \( L_{k1} \) and a DC resistance \( DCR_1 \), and a second of said coupled output inductors having a leakage inductance \( L_{k2} \) and a DC resistance \( DCR_2 \); and

14. An RC circuit connected in parallel with the first of the coupled output inductors, wherein the RC circuit comprises a resistor having a resistance \( R_1 \) and a capacitor having a capacitance \( C_1 \) connected in series, and wherein the RC circuit is constructed and arranged to have an \( R_1C_1 \) time constant approximately equal to \( L_{k1}/DCR_1 \).

15. The N-phase voltage regulator of claim 18, wherein each phase comprises a buck regulator.

16. The voltage regulator of claim 11, wherein the RC circuit has an RC time constant equal to
\[
\frac{L_{\text{in}}}{(DCR_1 + \frac{DCR}{N})}
\]
to within 10%.

17. The voltage regulator of claim 13, wherein the voltage regulator comprises N voltage buffers or amplifiers receiving voltages from across capacitors in the N RC circuits, and wherein the voltage adder adds voltages from the N voltage buffers or amplifiers.

18. An N-phase voltage regulator, wherein each phase includes:
(a) a plurality of coupled output inductors, constructed and arranged such that each of the coupled output inductors is coupled to at least one other of the output inductors, a first of said coupled output inductors having a leakage inductance \( L_{k1} \) and a DC resistance \( DCR_1 \), and a second of said coupled output inductors having a leakage inductance \( L_{k2} \) and a DC resistance \( DCR_2 \); and

19. The N-phase voltage regulator of claim 18, wherein each phase comprises a buck regulator.

20. The N-phase voltage regulator of claim 18, further comprising:
another RC circuit, connected in parallel with another of said mutually coupled output inductors, wherein said another RC circuit comprises a resistor having a resistance \( R_2 \) and a capacitor having a capacitance \( C_2 \) connected in series, and wherein said another RC circuit is constructed and arranged to have an RC time constant approximately equal to \( L_{k2}/DCR_2 \); and

a voltage adder for adding voltages across the respective capacitors in the RC circuits.