US 20130293207A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2013/0293207 A1

(43) Pub. Date: Nov. 7, 2013

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(54) **POWER SUPPLY WITH A MAGNETICALLY UNCOUPLED PHASE AND AN ODD NUMBER OF MAGNETICALLY COUPLED PHASES, AND CONTROL FOR A POWER SUPPLY WITH MAGNETICALLY COUPLED AND MAGNETICALLY UNCOUPLED PHASES**

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(21) Appl. No.: **13/852,973**

(22) Filed: **Mar. 28, 2013**

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/136,014, filed on Jul. 20, 2011, now abandoned.

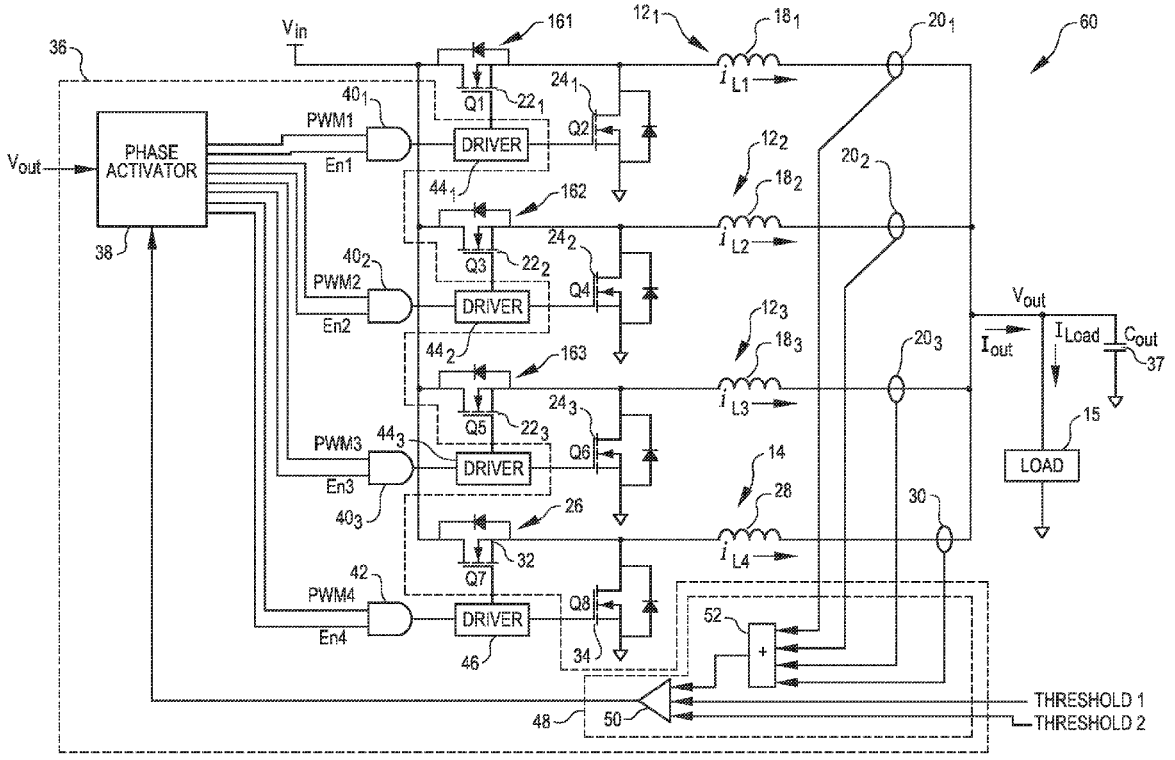
Publication Classification

(51) **Int. Cl.**
G05F 1/46 (2006.01)

(52) **U.S. Cl.**
CPC *G05F 1/46* (2013.01)
USPC **323/272**

(57) **ABSTRACT**

An embodiment of a power supply includes an input node operable to receive an input voltage, an output node operable to provide a regulated output voltage, an odd number of magnetically coupled phase paths each coupled between the input and output nodes, and a first magnetically uncoupled phase path coupled between the input and output nodes. Such a power supply may improve its efficiency by activating different combinations of the coupled and uncoupled phase paths depending on the load conditions. For example, the power supply may activate only an uncoupled phase path during light-load conditions, may activate only coupled phase paths during moderate-load conditions, and may activate both coupled and uncoupled phase paths during heavy-load conditions and during a step-up load transient.



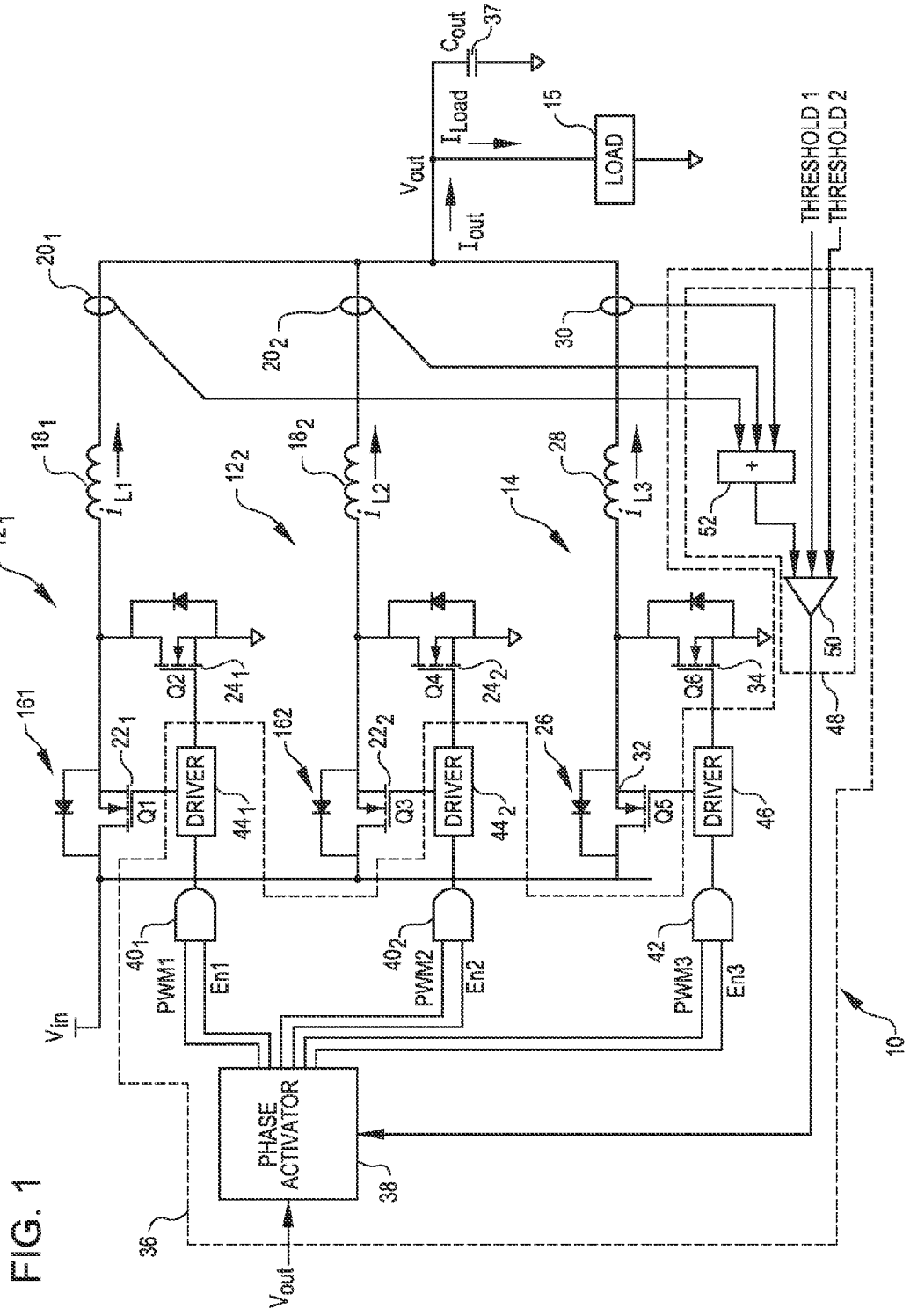

C_{out} 37
I_{Load}
15
LOAD
V_{out}
I_{out}
THRESHOLD 1
THRESHOLD 2
20_1
20_2
30
18_1
18_2
28
I_{L1}
I_{L2}
I_{L3}
12_1
12_2
14
52
+
50
48
34
24_1
24_2
Q2
Q4
Q6
16_1
16_2
26
22_1
22_2
32
Q1
Q3
Q5
DRIVER
44_1
44_2
46
40_1
40_2
42
PWM1
PWM2
PWM3
En1
En2
En3
V_{in}
10
PHASE ACTIVATOR
38
36
V_{out}

FIG. 1

FIG. 2

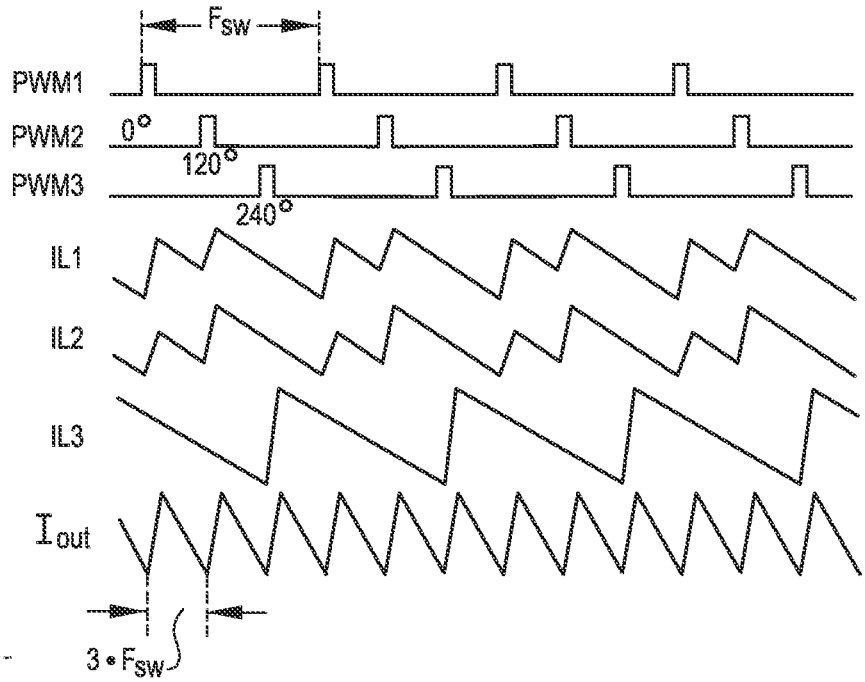
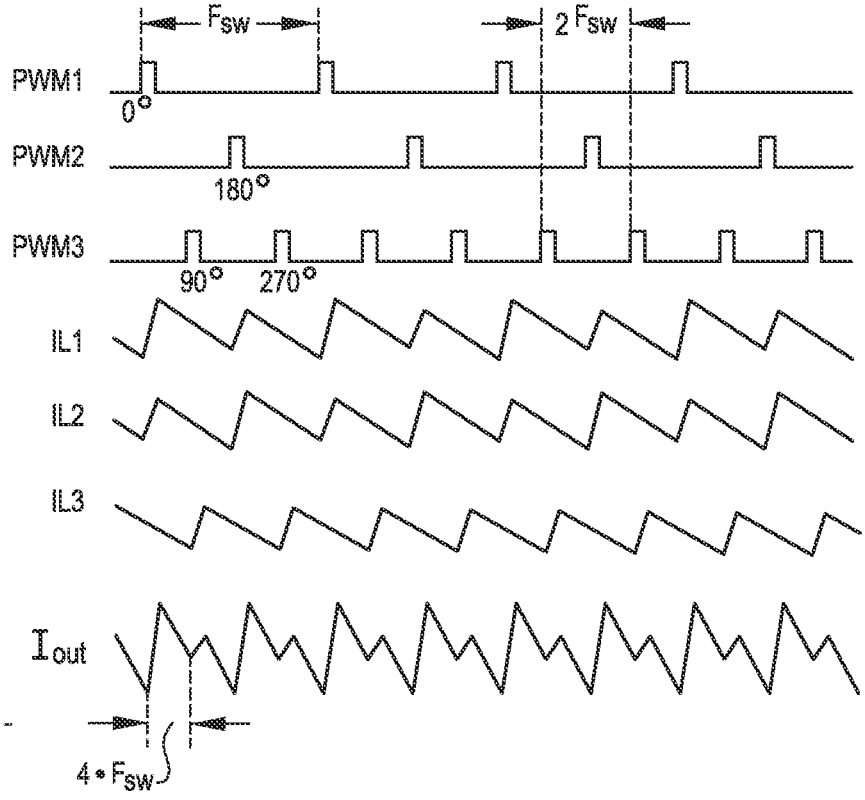

Fsw
PWM1
PWM2
0°
120°
PWM3
240°
IL1
IL2
IL3
Iout
3 • Fsw

FIG. 3


Fsw
2 Fsw
PWM1
0°
PWM2
180°
PWM3
90°
270°
IL1
IL2
IL3
Iout
4 • Fsw

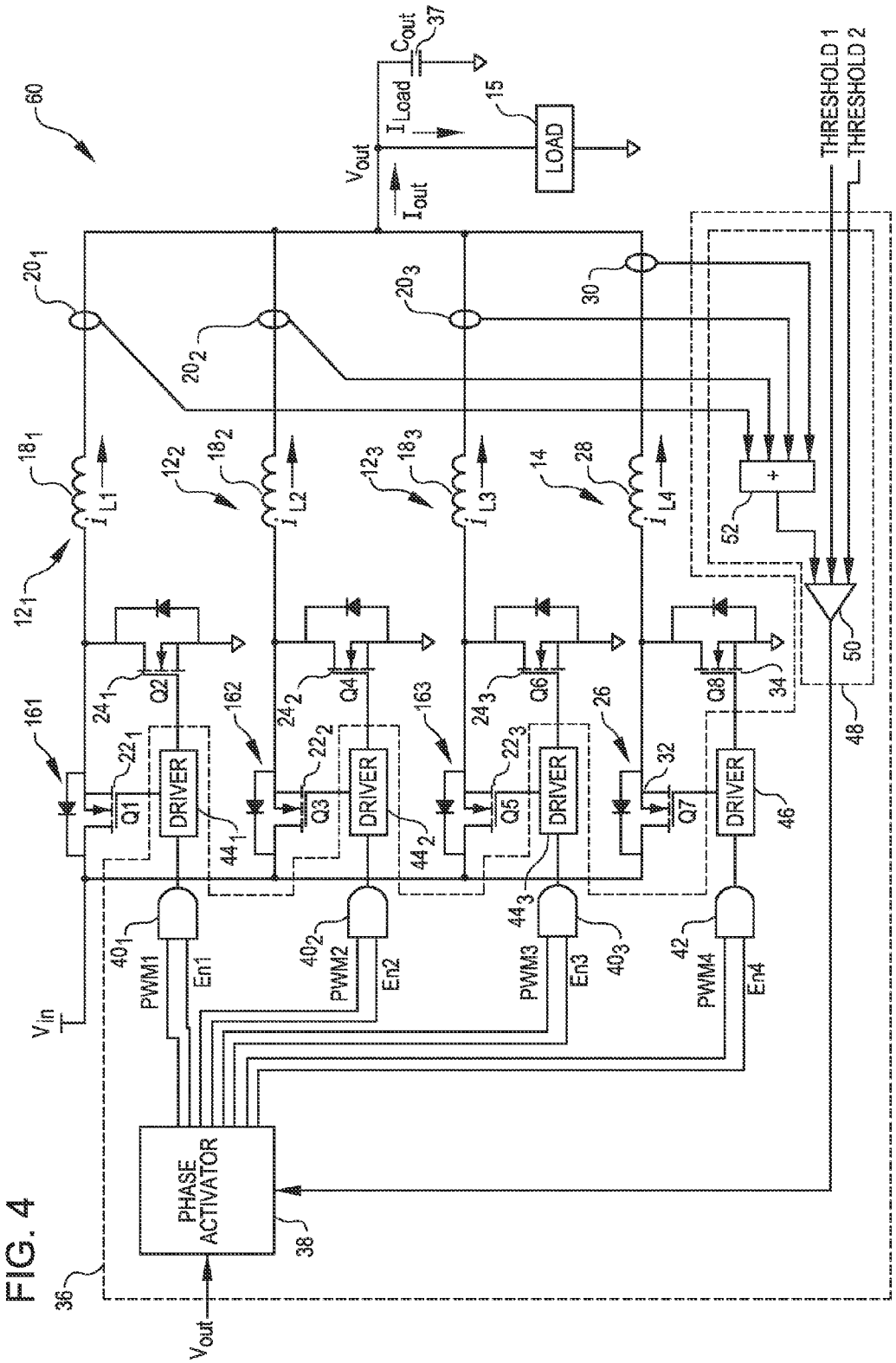

60
Vout
Cout
37
ILoad
15
LOAD
Iout
THRESHOLD 1
THRESHOLD 2
20 1
20 2
20 3
30
18 1
18 2
18 3
12 1
12 2
12 3
14
28
i L1
i L2
i L3
i L4
52
+
50
48
34
161
162
163
26
24 1
24 2
24 3
22 1
22 2
22 3
32
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
DRIVER
44 1
44 2
44 3
46
40 1
40 2
40 3
42
PWM1
PWM2
PWM3
PWM4
En1
En2
En3
En4
Vin
PHASE ACTIVATOR
38
36
Vout

FIG. 4

FIG. 5

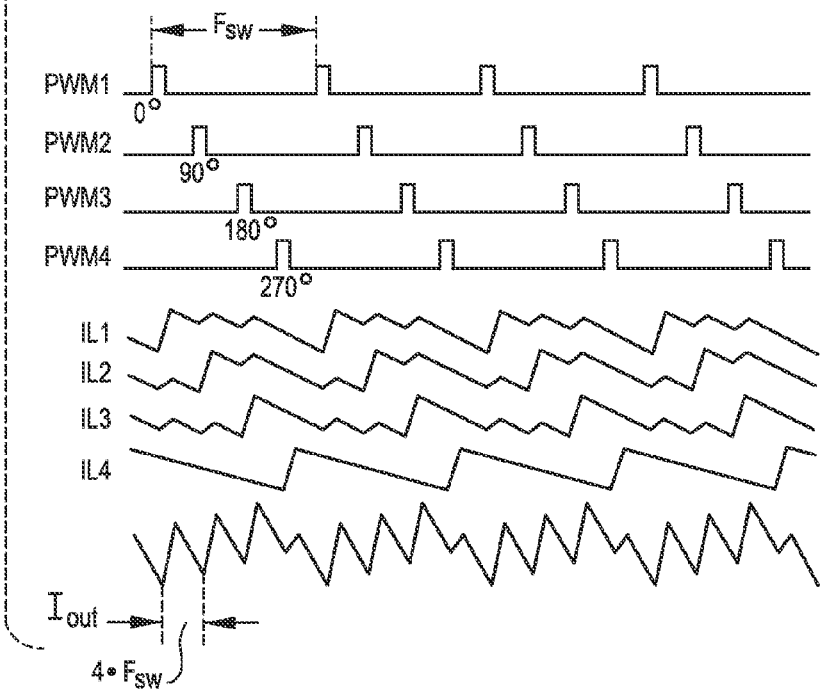

Fsw
PWM1
0°
PWM2
90°
PWM3
180°
PWM4
270°
IL1
IL2
IL3
IL4
Iout
4*Fsw

FIG. 6

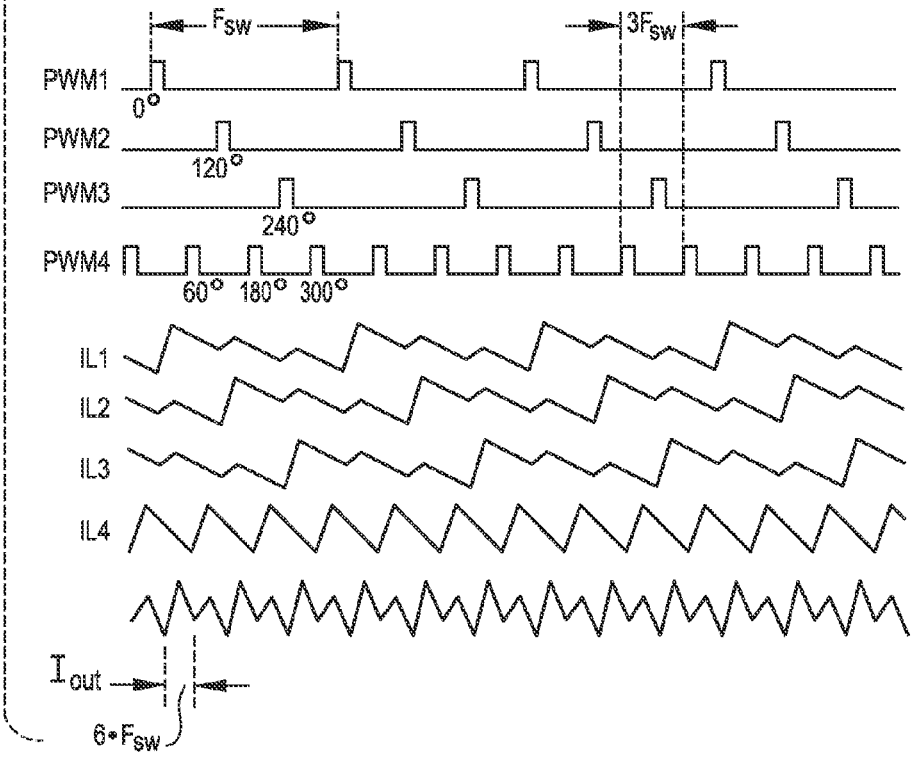

Fsw
3Fsw
PWM1
0°
PWM2
120°
PWM3
240°
PWM4
60°
180°
300°
IL1
IL2
IL3
IL4
Iout
6*Fsw

FIG. 7

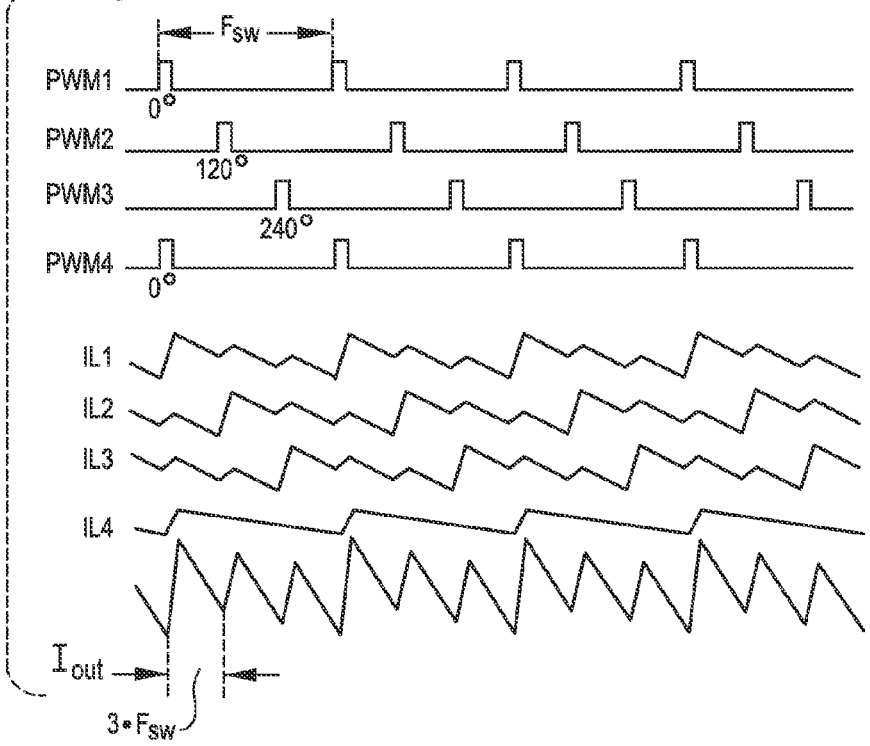

F_{sw}
PWM1
0°
PWM2
120°
PWM3
240°
PWM4
0°
IL1
IL2
IL3
IL4
I_{out}
$3 \cdot F_{sw}$

FIG. 8

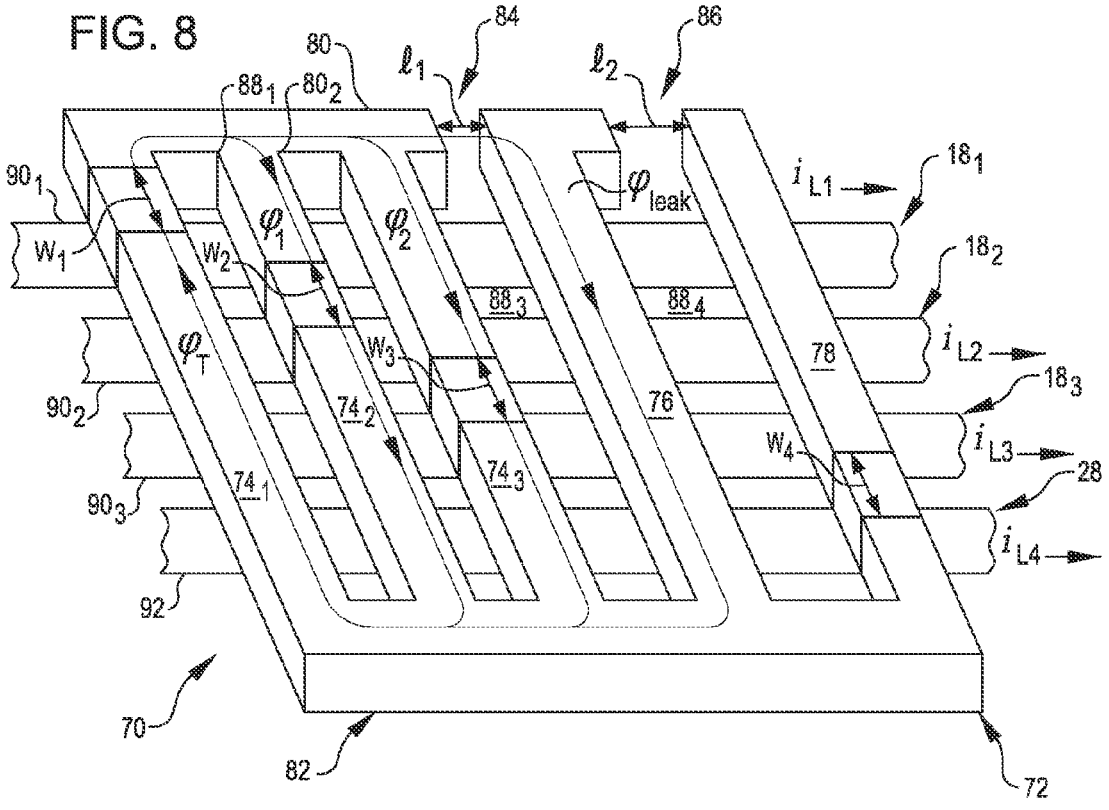

84
80
86
ℓ_1
ℓ_2
88_1
80_2
90_1
W_1
φ_1
W_2
φ_2
φ_{leak}
i_{L1}
18_1
18_2
88_3
88_4
φ_T
W_3
78
i_{L2}
18_3
90_2
74_2
76
W_4
i_{L3}
28
90_3
74_1
74_3
i_{L4}
92
70
82
72

FIG. 9

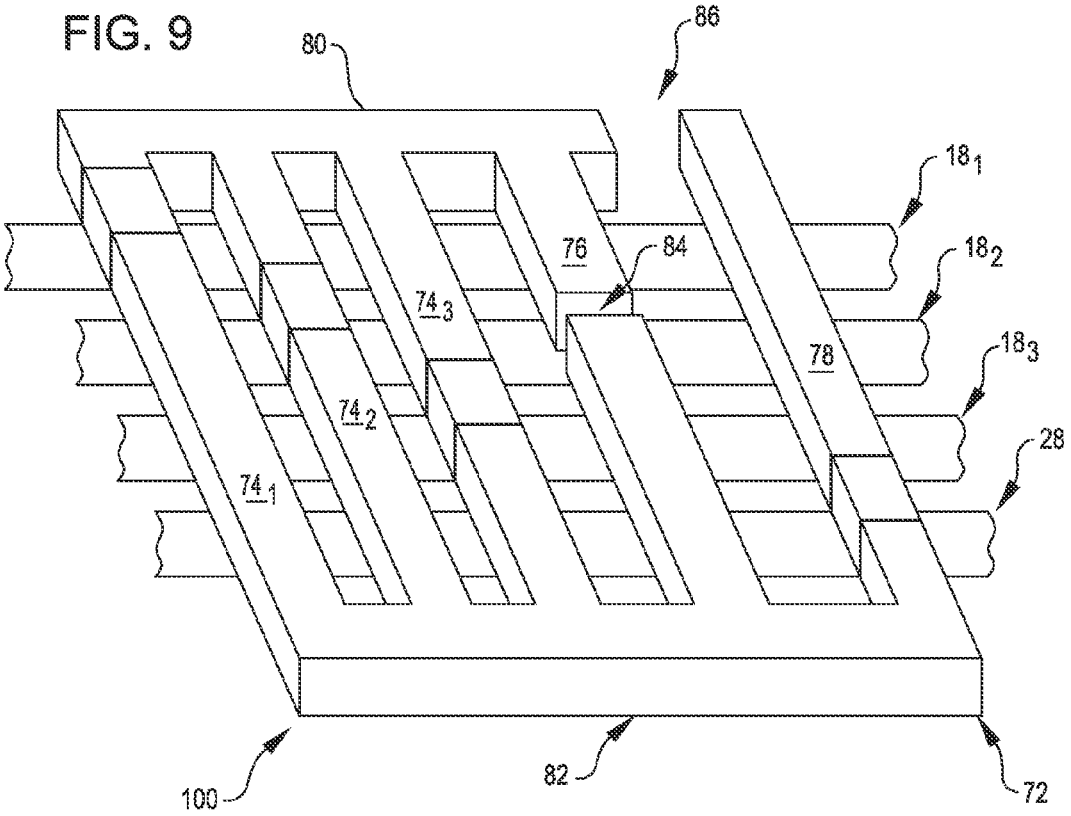

80
86
18_1
18_2
18_3
28
76
84
74_3
74_2
74_1
78
100
82
72

FIG. 10

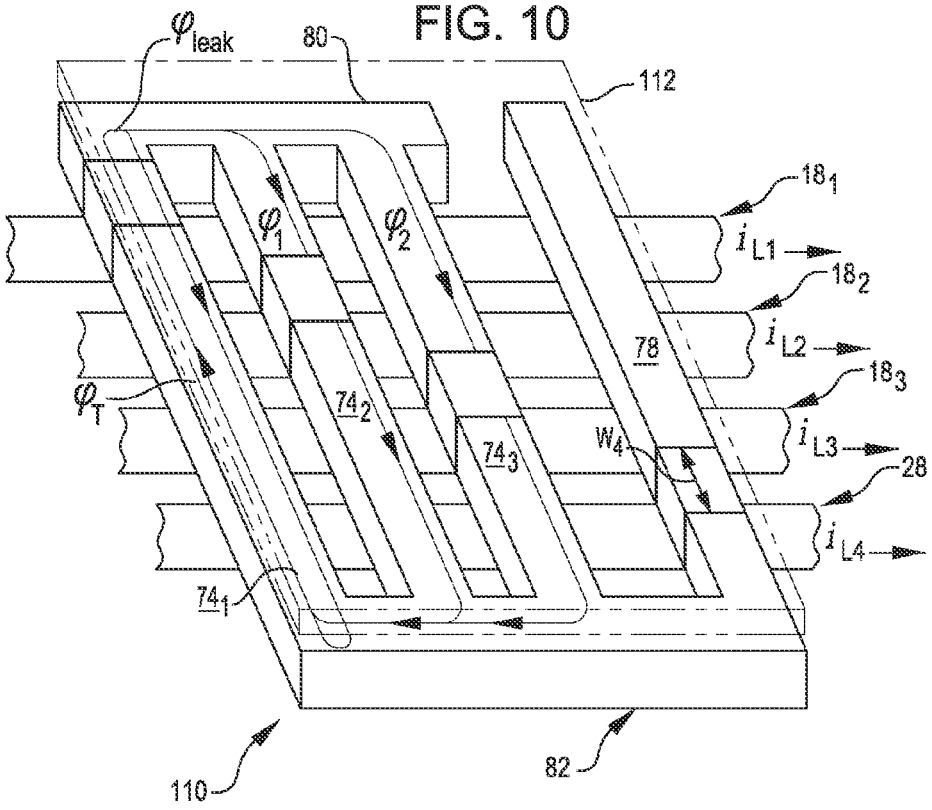

φ_{leak}
80
112
18_1
φ_1
φ_2
i_{L1}
18_2
i_{L2}
78
18_3
φ_T
74_2
74_3
W_4
i_{L3}
28
i_{L4}
74_1
110
82

FIG. 11

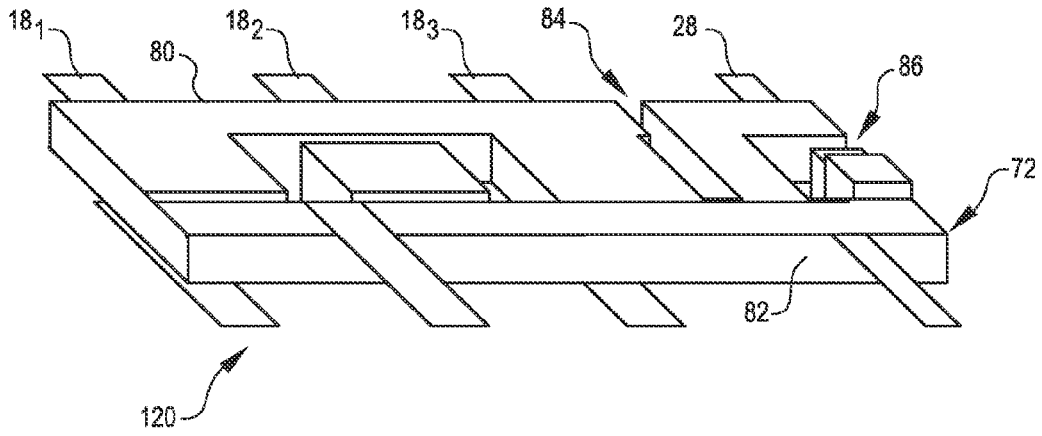
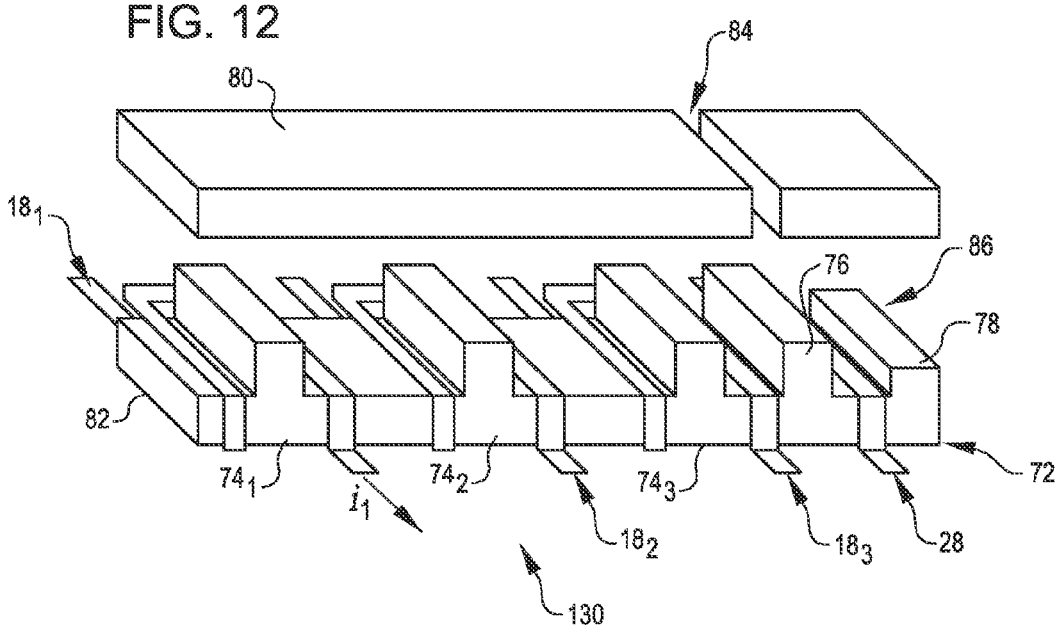

18_1
80
18_2
18_3
84
28
86
72
82
120

FIG. 12


84
80
18_1
86
76
78
82
74_1
74_2
74_3
72
i_1
18_2
18_3
28
130

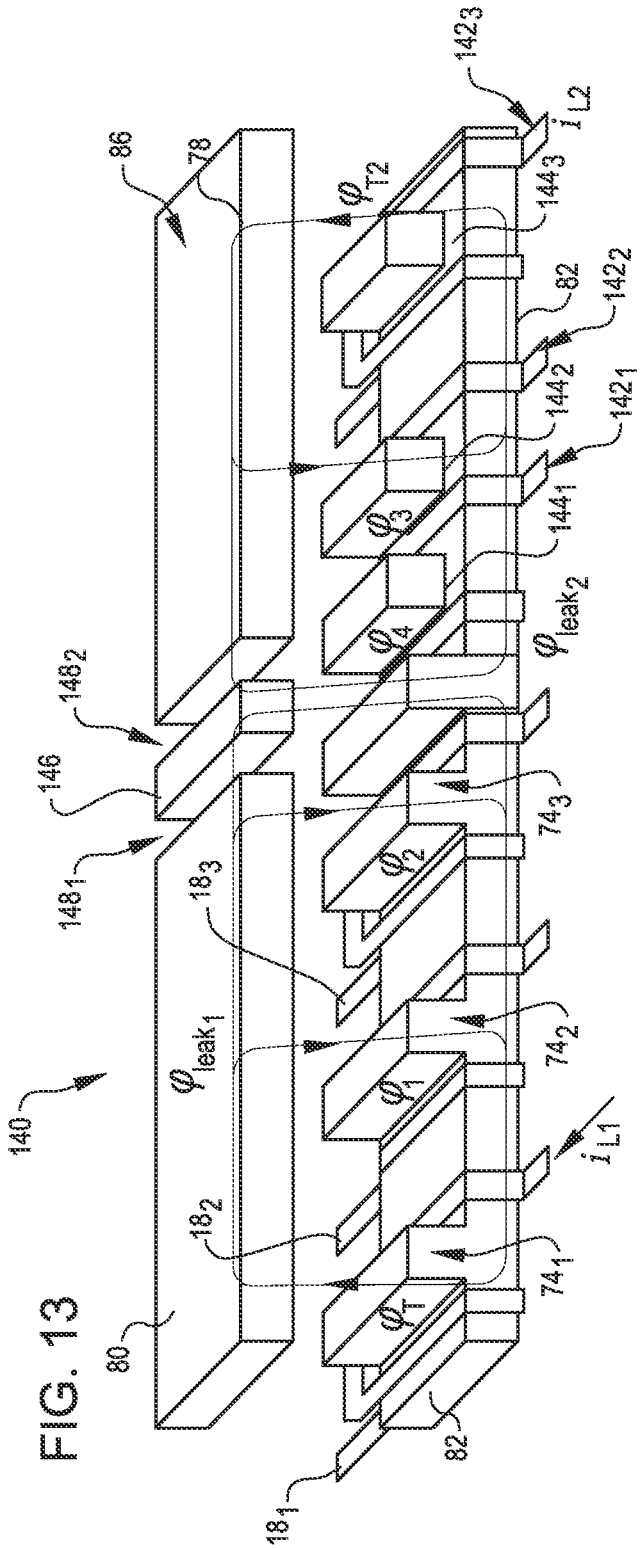
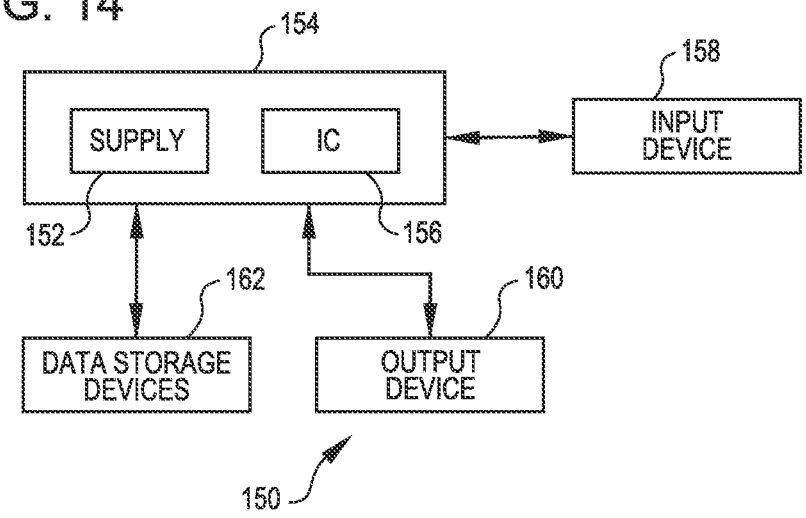

140
80
86
78
82
82
18_1
18_2
18_3
142_3
142_2
142_1
144_3
144_2
144_1
148_2
148_1
146
74_3
74_2
74_1
i_{L2}
i_{L1}
φ_{T2}
φ_{T1}
φ_{leak_1}
φ_{leak_2}
φ_1
φ_2
φ_3
φ_4

FIG. 13

FIG. 14


154
158
SUPPLY
IC
INPUT DEVICE
152
156
162
160
DATA STORAGE DEVICES
OUTPUT DEVICE
150

POWER SUPPLY WITH A MAGNETICALLY UNCOUPLED PHASE AND AN ODD NUMBER OF MAGNETICALLY COUPLED PHASES, AND CONTROL FOR A POWER SUPPLY WITH MAGNETICALLY COUPLED AND MAGNETICALLY UNCOUPLED PHASES

PRIORITY CLAIM

[0001] The present application is a Continuation-In-Part of copending U.S. patent application Ser. No. 12/136,014 filed Jun. 9, 2008; which application claims the benefit of U.S. Provisional Patent Application Ser. No. 60/933,949, filed Jun. 8, 2007, now expired; all of the foregoing applications are incorporated by reference herein in their entireties.

CROSS-RELATED APPLICATIONS

[0002] The present application is related to U.S. patent application Ser. No. 12/136,018 entitled COUPLED-INDUCTOR CORE FOR UNBALANCED PHASE CURRENTS, filed on Jun. 9, 2008, and is related to U.S. patent application Ser. No. 12/136,023 entitled INDUCTOR ASSEMBLY HAVING A CORE WITH MAGNETICALLY ISOLATED FORMS, filed on Jun. 9, 2008, now U.S. Pat. No. 8,179,116, issued on May 15, 2012; all of the foregoing applications have a common owner and are incorporated herein by reference in theirs entireties.

SUMMARY

[0003] This Summary is provided to introduce, in a simplified form, a selection of concepts that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter.

[0004] An embodiment of a power supply includes an input node operable to receive an input voltage, an output node operable to provide a regulated output voltage, an odd number of magnetically coupled phase paths each coupled between the input and output nodes, and a first magnetically uncoupled phase path coupled between the input and output nodes.

[0005] Such a power supply may improve its efficiency by activating different combinations of the coupled and uncoupled phases depending on the load conditions. For example, the power supply may activate only an uncoupled phase path during light-load conditions, may activate only coupled phase paths during moderate-load conditions, and may activate both coupled and uncoupled phase paths during heavy-load conditions and during a step-up load transient.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** is a schematic diagram of an embodiment of a multiphase buck converter that includes an even number of magnetically coupled phase paths and a magnetically uncoupled phase path.

[0007] FIG. **2** is a timing diagram of phase switching signals and phase currents generated by the buck converter of FIG. **1** while operating according to a first embodiment of a switching technique.

[0008] FIG. **3** is a timing diagram of phase switching signals and phase currents generated by the buck converter of FIG. **1** while operating according to a second embodiment of a switching technique.

[0009] FIG. **4** is a schematic diagram of another embodiment of a multiphase buck converter that includes an odd number of magnetically coupled phase paths and at least one magnetically uncoupled phase path.

[0010] FIG. **5** is a timing diagram of phase switching signals and phase currents generated by the buck converter of FIG. **4** while operating according to the first embodiment of a switching technique.

[0011] FIG. **6** is a timing diagram of phase switching signals and phase currents generated by the buck converter of FIG. **4** according to the second embodiment of a switching technique.

[0012] FIG. **7** is a timing diagram of phase switching signals and phase currents generated by the buck converter of FIG. **4** while operating according to a third embodiment of a switching technique.

[0013] FIGS. **8-13** are diagrams of embodiments of inductor assemblies that may provide the phase windings of the buck converters of FIGS. **1** and **4**.

[0014] FIG. **14** is a block diagram of a system that may incorporate one or both of the buck converters of FIGS. **1** and **4**.

DETAILED DESCRIPTION

[0015] Magnetically coupled inductors are used in circuits such as multiphase switching power supplies. For example, using coupled inductors in a multiphase buck converter may allow a designer to reduce the size (e.g., the component count and component values) of the output filter, and thus the size of the converter, for a given transient response and a given amplitude of the output ripple voltage.

[0016] Magnetically uncoupled inductors are also used in circuits such as multiphase switching power supplies. Although using uncoupled inductors in a multiphase power supply may increase the size of the supply for a given transient response and for a given amplitude of the output ripple voltage as compared to a coupled-inductor (CI) multiphase supply, an uncoupled-inductor (UI) multiphase supply may be more efficient than a CI multiphase supply under certain load conditions.

[0017] FIG. **1** is a schematic diagram of an embodiment of a multiphase buck converter **10**, which includes magnetically coupled phases $\mathbf{12}_1$-$\mathbf{12}_2$ and a magnetically uncoupled phase **14** for driving a load (e.g., an integrated circuit such as a processor) **15** with a regulated output voltage V_{out}. As further discussed below, selectively activating the coupled and uncoupled phases **12** and **14** in response to the load may improve the efficiency of the buck converter **10** as compared to purely CI and purely UI converters. Improving the efficiency of the buck converter **10** may not only reduce the amount of energy dissipated by the converter, but, by reducing the amount of heat generated by the converter, may also reduce the amount of energy required to cool a system (e.g., a computer) in which the converter is disposed.

[0018] The magnetically coupled phase $\mathbf{12}_1$ includes a switching circuit $\mathbf{16}_1$, a winding $\mathbf{18}_1$, and a current sensor $\mathbf{20}_1$. The switching circuit $\mathbf{16}_1$ includes a high-side transistor $\mathbf{22}_1$ and a low-side transistor $\mathbf{24}_1$. The winding $\mathbf{18}_1$ includes a conductor that is wound about a magnetically permeable core (not shown in FIG. **1**). And the current sensor $\mathbf{20}_1$ may be any conventional current sensor, for example, a resistor in series with the winding $\mathbf{18}_{11}$, or a series combination of a resistor and a capacitor in parallel with the winding.

[0019] Similarly, the magnetically coupled phase $\mathbf{12}_2$ includes a switching circuit $\mathbf{16}_2$, a winding $\mathbf{18}_2$, and a current sensor $\mathbf{20}_2$. The switching circuit $\mathbf{16}_2$ includes a high-side transistor $\mathbf{22}_2$ and a low-side transistor $\mathbf{24}_2$. The winding $\mathbf{18}_2$ includes a conductor that is wound about the same magnetically permeable core (not shown in FIG. **1**) as is the winding $\mathbf{18}_1$. And the current sensor $\mathbf{20}_2$ may be similar to the current sensor $\mathbf{20}_1$.

[0020] The magnetically uncoupled phase **14** includes a switching circuit **26**, a winding **28**, and a current sensor **30**. The switching circuit **26** includes a high-side transistor **32** and a low-side transistor **34**. As discussed below in conjunction with FIGS. **8-13**, the winding **28** includes a conductor that may be wound about the same core (not shown in FIG. **1**) as are the windings $\mathbf{18}_1$ and $\mathbf{18}_2$. And the current sensor **28** may be similar to the current sensors $\mathbf{20}_1$ and $\mathbf{20}_2$.

[0021] In addition to the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14**, the converter **10** includes a power-supply controller **36**, which may be disposed on an integrated circuit (IC), and an output filter capacitor C_{out} **37**.

[0022] The controller **36** includes a phase activator **38**, phase enable circuits (AND gates in the illustrated embodiment) $\mathbf{40}_1$, $\mathbf{40}_2$, and **42**, phase drivers $\mathbf{44}_1$, $\mathbf{44}_2$, and **46**, and an output-current detector **48**. Under steady-state operating conditions, the average output current I_{out_avg} equals the load current I_{Load}; hence, changes in I_{Load} are reflected in corresponding changes in the output current I_{out}.

[0023] The phase activator **38** generates switching signals PWM**1**, PWM**2**, and PWM**3** for the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14**, respectively, and generates enable signals EN**1**, EN**2**, and EN**3**. If the signal EN**1** is logic 1, then the enable circuit $\mathbf{40}_1$ allows the switching signal PWM**1** to propagate to the driver $\mathbf{44}_1$, and thus enables the phase activator **38** to activate the phase $\mathbf{12}_1$. Likewise, if the signal EN**1** is logic 0, then the enable circuit $\mathbf{40}_1$ prohibits the switching signal PWM**1** from propagating to the driver $\mathbf{44}_1$, and thus disables, i.e., deactivates, the phase $\mathbf{12}_1$. The enable circuits $\mathbf{40}_2$ and **43** operate similarly in response to signals EN**2** and EN**3**, respectively.

[0024] The drivers **44** and **46** may each include an inverter. For example, the driver **44**, may include an inverter having an input node coupled to the output of the AND gate $\mathbf{40}_1$ and to the gate of the high-side transistor $\mathbf{22}_1$, and having an output node coupled to the gate of the low-side transistor $\mathbf{24}_1$. The inverters of the drivers $\mathbf{44}_2$ and **46** may be coupled in a similar manner.

[0025] The output-current detector **48** includes a window comparator **50** and a summer **52**. The comparator **50** receives from the summer **52** a sum signal representing the total output current I_{out}, compares the sum signal to two reference voltages Threshold**1** and Threshold**2** (Threshold**2**>Threshold**1**), and provides the result of the comparison to the phase activator **38**. For example, if the sum signal is less than or equal to Threshold**1**, then the phase activator **38** generates EN**1**=EN**2**=logic 0 and EN**3**=logic 1 to deactivate the coupled phases $\mathbf{12}_1$ and $\mathbf{12}_2$ and to activate the uncoupled phase **14**. If the sum signal is greater than Threshold**1** and less than Threshold**2**, then the phase activator **38** generates EN**1**=EN**2**=logic 1 and EN**3**=logic 0 to activate the coupled phases $\mathbf{12}_1$ and $\mathbf{12}_2$ and to deactivate the uncoupled phase **14**. And, if the sum signal is greater than Threshold**2**, then the phase activator **38** generates EN**1**=EN**2**=EN**3**=1 to activate all of the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14**. The summer **52** may include, for example, a summing node of an operational amplifier (not shown in FIG. **1**), and Threshold**1** and Threshold**2** may be generated externally to the power-supply controller **36**, may be generated internally, or may be generated internally and adjustable externally.

[0026] The power-supply controller **36** may include other circuitry that is omitted from FIG. **1** for brevity. For example, the controller **36** may include circuitry that causes each of the active ones of the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14** to carry a respective percentage of I_{out}. Where such circuitry causes each of the active ones of the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14** to carry equal percentages of I_{out}, then the active phases may be described as carrying balanced currents. Examples of such circuitry are described in U.S. Pat. No. 6,278,263, which is incorporated by reference. And where such circuitry causes each of the active ones of the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14** to carry unequal percentages of I_{out}, then the active phases may be described as carrying unbalanced currents. Examples of such circuitry are described in U.S. patent application Ser. No. 12/136,018, which is incorporated by reference.

[0027] Operation of the multiphase buck converter **10** is discussed according to an example where Threshold**1** has a level that corresponds to I_{out}~10 Amperes (A), and where Threshold**2** has a level that corresponds to I_{out}~50 A.

[0028] In a first mode of operation where the summing signal from the comparator **52** is between Threshold**1** and Threshold**2**, and thus ~10 A<I_{out}<~50 A, the phase activator **38** activates the coupled phases $\mathbf{12}_1$ and $\mathbf{12}_2$, and deactivates the uncoupled phase **14** such that the converter **10** has its highest efficiency for this range of I_{out}. To activate the phases $\mathbf{12}_1$ and $\mathbf{12}_2$, the phase activator **38** generates EN**1**=EN**2**=1 so as to cause the switch circuits $\mathbf{16}_1$ and $\mathbf{16}_2$ to switch the coupled phases $\mathbf{12}_1$ and $\mathbf{12}_2$ at a switching frequency and with respective duty cycles sufficient to regulate V_{out} to a specified voltage level, such as 1.8 Volts (V), which is less than an input voltage V_{in} such as 3.3 V. For example, where the phases have equivalent electrical characteristics and $\mathbf{12}_1$ and $\mathbf{12}_2$ carry balanced currents, i.e., equal portions (here half) of the average I_{out}, and have similar electrical characteristics (e.g., inductance) then the phase activator **38** causes the switching circuits $\mathbf{16}_1$ and $\mathbf{16}_2$ to switch the phases $\mathbf{12}_1$ and $\mathbf{12}_2$ with substantially the same duty cycle. And to deactivate the phase **14**, the phase activator **38** generates EN**3**=0 so that the switching circuit **26** puts both the high-side and low-side transistors **32** and **34** in a high-impedance state.

[0029] In a second mode of operation where the summing signal is less than or equal to Threshold**1** (and thus also less than Threshold**2**), and thus I_{out}~10 A, the phase activator **38** deactivates the coupled phases $\mathbf{12}_1$ and $\mathbf{12}_2$, and activates the uncoupled phase **14** such that the converter **10** has its highest efficiency for this range of I_{out}. To activate the phase **14**, the phase activator **38** generates EN**3**=1 so as to cause the switch circuit **26** to switch the uncoupled phase **14** at a switching frequency and with a duty cycle sufficient to regulate V_{out} to the specified voltage level. And to deactivate the coupled phases $\mathbf{12}_1$ and $\mathbf{12}_2$, the phase activator **38** generates EN**1**=EN**2**=0 so that the switching circuits $\mathbf{16}_1$ and $\mathbf{16}_2$ put both the high-side and low-side transistors $\mathbf{22}_1$, $\mathbf{22}_2$, $\mathbf{24}_1$, and $\mathbf{24}_2$ in a high-impedance state.

[0030] In a third mode of operation where the summing signal is greater than or equal to Threshold**2** (and thus also greater than Threshold**1**), and thus I_{out}~50 A, the phase activator **38** activates the coupled phases $\mathbf{12}_1$ and $\mathbf{12}_2$ and the uncoupled phase **14** such that the converter **10** has its highest efficiency for this range of I_{out}. To activate the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14**, the phase activator **38** generates EN**1**=EN**2**=EN**3**=1

so as to cause the switch circuits **16**$_1$, **16**$_2$, and **26** to switch each of the phases **12**$_1$, **12**$_2$, and **14** at respective switching frequencies and with respective duty cycles sufficient to regulate V_{out} to the specified voltage level.

[0031] Still referring to FIG. **1**, in summary, by selectively activating the coupled phases **12**$_1$ and **12**$_2$ and the uncoupled phase **14** in response to the level of I_{out}, the phase activator **38** may allow the converter **10** to operate at its highest efficiency for each identifiable load level.

[0032] Alternate embodiments of the multiphase buck converter **10** are contemplated. For example, although the converter **10** is described as having two coupled phases **12**$_1$ and **12**$_2$ and a single uncoupled phase **14**, the converter may have more than two coupled phases and more than one uncoupled phase—an example of a multiphase buck converter having three coupled phases and a single uncoupled phase is described below in conjunction with FIG. **4**. Furthermore, although shown as being external to the power-supply controller **36**, the transistors **22**, **24**, **32**, and **34** may be disposed on the same IC as the other components of the controller **36**, as may be any of the other components (e.g., windings **18**, current sensors **20**) of the converter **10** shown external to the controller in FIG. **1**. Moreover, instead of activating or deactivating all of the coupled phases **12** together, the phase activator **38** may activate fewer than all of the coupled phases (with or without an active uncoupled phase) in response to more than two threshold levels. A technique for activating fewer than all coupled phases is disclosed in U.S. patent application Ser. No. 11/519,516, filed Sep. 12, 2006, which is incorporated by reference. In addition, although described in conjunction with a buck converter, the above-described concepts for selectively activating coupled and uncoupled phases may be useful in any type of multiphase power supply. Furthermore, although the buck converter **10** is described as having a pulse-width-modulated (PWM) architecture, the converter may have another switching architecture such as a constant-on-time architecture. Moreover, the detector **48** may be omitted, and the load **15** may provide a load signal to the phase activator **38**, the load signal indicating the load level. For example, the load signal may be similar to the signal that would otherwise be generated by the comparator **50**. Or, the load **15** may provide the load signal even when the detector **48** is present. In either case, the load signal may give the phase activator **38** advance notice of a significant load change that will cause the phase activator to activate a combination of CI and UI phases different from the current combination. Therefore, in response to the load signal, the phase activator **38** may begin to change the combination of active phases before the load **15** changes, and thus may reduce or eliminate load-transient-induced overshoot and undershoot on V_{out}. In addition, the phase-enable circuits **40** and **42** may include circuitry other than, or in addition to, NAND gates. Furthermore, although shown as MOS transistors, the transistors **22**, **24**, **32**, and **34** may be bipolar transistors, or the transistors **24** and **34** may be replaced with diodes.

[0033] FIG. **2** is a timing diagram of the signals PWM**1**, PWM**2**, and PWM**3** of FIG. **1**, the respective phase currents IL**1**, IL**2**, and IL**3** through the phases **12**$_1$, **12**$_2$, and **14** of FIG. **1**, and I_{out} while the converter **10** is operating in the above-described third mode and according to a first embodiment of a switching technique. These signals may not be drawn to scale, however. Furthermore, in this example, the signals PWM**1**, PWM**2**, and PWM**3** (or amplified versions thereof) respectively drive high-side transistors **22**$_1$, **22**$_2$ and **32**, and the inverses of these signals respectively drive the low-side transistors **24**$_1$, **24**$_2$, and **34**. Moreover, although shown as having the same duty cycle, the signals PWM**1**, PWM**2**, and PWM**3** may have different duty cycles.

[0034] Referring to FIGS. **1** and **2**, the phase activator **38** implements this switching technique by causing the switching circuits **16**$_1$, **16**$_2$, and **26** to switch the active ones of the phases **12**$_1$, **12**$_2$, and **14** at a frequency F_{sw} and at relative phase shifts of 360°/NA, where NA=number of active coupled and uncoupled phases. For example, during the third operating mode when all three phases **12**$_1$, **12**$_2$, and **14** are active, the switching circuits **16**$_1$, **16**$_2$, and **26** switch the phases at relative phase shifts of 0°, 120°, and 240° as shown in FIG. **2**. During the second operating mode when only the two coupled phases **12**$_1$ and **12**$_2$ are active, then the switching circuits **16**$_1$ and **16**$_2$ switch the coupled phases at frequency F_{sw} and relative phase shifts of 0° and 180°. And during the first operating mode when only the uncoupled phase **14** is active, then the switching circuit **26** switches the uncoupled phase at frequency F_{sw}.

[0035] With this switching technique, the ripple frequency of I_{out}, and thus the ripple frequency of V_{out}, approximately equals $NA \cdot F_{sw}$.

[0036] Still referring to FIG. **2**, alternate embodiments of the described switching technique are contemplated. Two or more of the active ones of the phases **12**$_1$, **12**$_2$, and **14** may be switched at the same relative phase shifts. For example, during the third operating mode of the converter **10** (FIG. **1**) while all of the phases **12**$_1$, **12**$_2$, and **14** are active, the phase **14** may be switched with the same relative phase shifts as phase **12**$_1$ or phase **12**$_2$. That is, PWM**3** may be aligned in time with PWM**1** or PWM**2**. Moreover, although the converter **10** includes only two coupled phases and one uncoupled phase, the described switching technique may be scaled for more than two coupled phases and for more than one uncoupled phase.

[0037] FIG. **3** is a timing diagram of the signals PWM**1**, PWM**2**, and PWM**3** of FIG. **1**, the respective phase currents IL**1**, IL**2**, and IL**3** through the phases **12**$_1$, **12**$_2$, and **14** of FIG. **1**, and I_{out} while the converter **10** of FIG. **1** is operating in the above-described third mode and according to a second embodiment of a switching technique. And as discussed above in conjunction with FIG. **3**, these signals may not be drawn to scale, and PWM**1**, PWM**2**, and PWM**3** may have a different duty cycles and respectively drive the high-side transistors **22**$_1$, **22**$_2$, and **32**.

[0038] Referring to FIGS. **1** and **3**, the phase activator **38** implements the second embodiment of a switching technique by causing the switching circuits **16**$_1$ and **16**$_2$ to switch the phases **12**$_1$ and **12**$_2$ at a frequency F_{sw} and at relative phase shifts of 360°/NAC, where NAC=the number of active coupled phases, and by causing the switching circuit **26** to switch the phase **14** at a frequency equal to $NAC \cdot F_{sw}$ and at phase shifts relative to F_{sw} of 360°/2(NAC). That is, the high-side transistor **32** switches "on" the phase **14** at times that are approximately centred between the times that the transistors **22**$_1$ and **22**$_2$ switch "on" the phases **12**$_1$ and **12**$_2$. For example, during the third mode of operation when all three phases **12**$_1$, **12**$_2$, and **14** are active, the switching circuits **16**$_1$ and **16**$_2$ switch the phases **12**$_1$ and **12**$_2$ at F_{sw} and at relative phase shifts of 0° and 180°, and the switching circuit **26** switches the phase **14** at $2 \cdot F_{sw}$ and at relative phase shifts of 90° and 270° as shown in FIG. **3**. During the second operating mode when only the two coupled phases **12**$_1$ and **12**$_2$ are active, the

switching circuits $\mathbf{16}_1$ and $\mathbf{16}_2$ switch the coupled phases at frequency F_{sw} and at relative phase shifts of 0° and 180°. And during the first operating mode when only the uncoupled phase **14** is active, then the switching circuit **26** switches the uncoupled phase at frequency F_{sw}, or, alternatively, at $2 \cdot F_{sw}$.

[0039] With the second switching technique, the ripple frequency of I_{out}, and thus the ripple frequency of V_{out}, approximately equals $2 \cdot NAC \cdot F_{sw}$. Also, in the third operating mode when all of the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and **14** are active, the ripple amplitude of I_{out}, and thus the ripple amplitude of V_{out}, may be less than when the converter **10** operates according to the first embodiment of the switching technique as discussed above in conjunction with FIG. **2**.

[0040] Still referring to FIG. **3**, alternate embodiments of the second switching technique are contemplated. For example, the phase **14** may be switched on at approximately the same times that the phases $\mathbf{12}_1$ and $\mathbf{12}_2$ are switched on; in the embodiment of FIG. **3**, this may be accomplished by shifting PWM**3** by 90° relative to F_{sw}, which would reduce the frequency of the I_{out}/V_{out} ripple to $2 \cdot F_{sw}$. Moreover, although the converter **10** of FIG. **1** includes only two coupled phases and one uncoupled phase, the second switching technique may be scaled for more than two coupled phases and for more than one uncoupled phase. Furthermore, the alternate embodiments discussed above in conjunction with FIG. **2** for the first switching technique may also be applicable to the second switching technique.

[0041] FIG. **4** is a schematic diagram of an embodiment of a multiphase buck converter **60**, which is similar to the buck converter **10** of FIG. **1** except that it includes an odd number (here three) of magnetically coupled phases $\mathbf{12}_1$-$\mathbf{12}_3$ instead of two coupled phases. In FIG. **4**, like numbers reference like components relative to the buck converter **10** of FIG. **1**. As discussed above in conjunction with FIG. **1** and as further discussed below, selectively activating the coupled and uncoupled phases **12** and **14** in response to the load **15** may improve the efficiency of the buck converter **60** as compared to purely CI and purely UI buck converters.

[0042] Operation of the converter **60** is discussed according to an example where Threshold**1** has a level that corresponds to I_{out}~10 A, and where Threshold**2** has a level that corresponds to I_{out}~50 A.

[0043] In a first mode of operation where the summing signal from the comparator **52** is between Threshold**1** and Threshold**2**, and thus ~10 A<I_{out}<~50 A, the phase activator **38** activates the coupled phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$, and deactivates the uncoupled phase **14** such that the converter **60** has its highest efficiency for this range of I_{out}. To activate the phases $\mathbf{12}_1$-$\mathbf{12}_3$, the phase activator **38** generates EN**1**=EN**2**=EN**3**=1 so as to cause the switch circuits $\mathbf{16}_1$-$\mathbf{16}_3$ to switch the coupled phases $\mathbf{12}_1$-$\mathbf{12}_3$ at a switching frequency and with respective duty cycles sufficient to regulate V_{out} to a specified voltage level, such as 1.8 V, which is less than an input voltage Vin such as 3.3 V. For example, where the phases $\mathbf{12}_1$-$\mathbf{12}_3$ carry balanced currents and have similar electrical characteristics, then the phase activator **38** causes the switching circuits $\mathbf{16}_1$-$\mathbf{16}_3$ to switch the phases $\mathbf{12}_1$-$\mathbf{12}_3$ with substantially the same duty cycle. And to deactivate the phase **14**, the phase activator **38** generates EN**4**=0 so that the switching circuit **26** puts both the high-side and low-side transistors **32** and **34** in a high-impedance state.

[0044] In a second mode of operation where the summing signal is less than or equal to Threshold**1** (and thus also less than Threshold**2**), and thus $I_{out} \leq$~10 A, the phase activator **38** deactivates the coupled phases $\mathbf{12}_1$-$\mathbf{12}_3$, and activates the uncoupled phase **14** such that the converter **60** has its highest efficiency for this range of I_{out}. To activate the phase **14**, the phase activator **38** generates EN**4**=1 so as to cause the switch circuit **26** to switch the uncoupled phase **14** at a switching frequency and with a duty cycle sufficient to regulate V_{out} to the specified voltage level. And to deactivate the coupled phases $\mathbf{12}_1$-$\mathbf{12}_3$, the phase activator **38** generates EN**1**=EN**2**=EN**3**=0 so that the switching circuits $\mathbf{16}_1$-$\mathbf{16}_3$ put the high-side and low-side transistors $\mathbf{22}_1$, $\mathbf{22}_2$, $\mathbf{22}_3$, $\mathbf{24}_1$, $\mathbf{24}_2$, and $\mathbf{24}_3$ in a high-impedance state.

[0045] In a third mode of operation where the summing signal is greater than or equal to Threshold**2** (and thus also greater than Threshold**1**), and thus $I_{out} \geq$~50 A, the phase activator **38** activates the coupled phases $\mathbf{12}_1$-$\mathbf{12}_3$ and the uncoupled phase **14** such that the converter **60** has its highest efficiency for this range of I_{out}. To activate the phases $\mathbf{12}_1$-$\mathbf{12}_3$ and **14**, the phase activator **38** generates EN**1**=EN**2**=EN**3**=EN**4**=1 so as to cause the switch circuits $\mathbf{16}_1$-$\mathbf{16}_3$ and **26** to switch each of the phases $\mathbf{12}_1$-$\mathbf{12}_3$ and **14** at respective switching frequencies and with respective duty cycles sufficient to regulate V_{out} to the specified voltage level.

[0046] Still referring to FIG. **4**, in summary, by selectively activating the coupled phases $\mathbf{12}_1$-$\mathbf{12}_3$ and the uncoupled phase **14** in response to the level of I_{out}, the phase activator **38** may allow the converter **60** to operate at its highest efficiency for each identifiable load level.

[0047] Furthermore, alternate embodiments of the multiphase buck converter **60** are contemplated. For example, although the converter **60** is described as having three coupled phases $\mathbf{12}_1$-$\mathbf{12}_3$ and a single uncoupled phase **14**, the converter may have more than three coupled phases and more than one uncoupled phase. Furthermore, the alternate embodiments described above for the buck converter **10** of FIG. **1** may also apply to the buck converter **60**.

[0048] FIG. **5** is a timing diagram of the signals PWM**1**, PWM**2**, PWM**3**, and PWM**4** of FIG. **4**, the respective phase currents IL**1**, IL**2**, IL**3**, and IL**4** through the phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$, and **14** of FIG. **4**, and I_{out} while the converter **60** is operating in the above-described third mode and according to the first embodiment of a switching technique. These signals may not be drawn to scale, and PWM**1**-PWM**4** may have different duty cycles and respectively drive the high-side transistors $\mathbf{22}_1$-$\mathbf{22}_3$ and **32**, respectively.

[0049] Referring to FIGS. **4** and **5**, the phase activator **38** implements this switching technique by causing the switching circuits $\mathbf{16}_1$, $\mathbf{16}_2$, $\mathbf{16}_3$, and **26** to switch the active ones of the phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$, and **14** at a frequency F_{sw} and at relative phase shifts of 360°/NACU, where NACU=number of active coupled and uncoupled phases. For example, during the third operating mode when all four phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$, and **14** are active, the switching circuits $\mathbf{16}_1$, $\mathbf{16}_2$, $\mathbf{16}_3$, and **26** switch the phases at relative phase shifts of 0°, 90°, 180°, and 270° as shown in FIG. **5**. During the second operating mode when only the three coupled phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$ are active, then the switching circuits $\mathbf{16}_1$-$\mathbf{16}_3$ switch the coupled phases at frequency F_{sw} and relative phase shifts of 0°, 120°, and 240°. And during the first operating mode when only the uncoupled phase **14** is active, then the switching circuit **26** switches the uncoupled phase at frequency F_{sw}.

[0050] With this switching technique, the ripple frequency of I_{out}, and thus the ripple frequency of V_{out}, approximately equals $NACU \cdot F_{sw}$.

[0051] Still referring to FIG. **5**, alternate embodiments of the described switching technique are contemplated. For example, the alternate embodiments described above in conjunction with FIGS. **2** and **3** may be applicable.

[0052] FIG. **6** is a timing diagram of the signals PWM**1**, PWM**2**, PWM**3**, and PWM**4** of FIG. **1**, the respective phase currents IL**1**, IL**2**, IL**3**, and IL**4** through the phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$, and **14** of FIG. **4**, and I_{out} while the converter **60** of FIG. **1** is operating in the above-described third mode and according to a second embodiment of a switching technique. These signals may not be drawn to scale, and PWM**1**, PWM**2**, PWM**3**, and PWM**4** may have different duty cycles and respectively drive the high-side transistors $\mathbf{22}_1$-$\mathbf{22}_3$ and **32**, respectively.

[0053] Referring to FIGS. **4** and **6**, the phase activator **38** implements the second embodiment of a switching technique by causing the switching circuits $\mathbf{16}_1$, $\mathbf{16}_2$, and $\mathbf{16}_3$ to switch the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$ at a frequency F_{sw} and at relative phase shifts of 360°/NAC, where NAC=the number of active coupled phases, and by causing the switching circuit **26** to switch the phase **14** at a frequency equal to NAC·F_{sw} and at a phase shifts relative to F_{sw} of 360°/2(NAC). That is, the high-side transistor **32** switches "on" the phase **14** at times that are approximately centred between the times that the circuits switches $\mathbf{22}_1$-$\mathbf{22}_3$ switch "on" the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$. For example, during the third mode of operation when all four phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$, and **14** are active, the switching circuits $\mathbf{16}_1$, $\mathbf{16}_2$, and $\mathbf{16}_3$ switch the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$ at F_{sw} and at a relative phase shifts of 0°, 120°, and 240°, and the switching circuit **26** switches the phase **14** at 3·F_{sw} and at a relative phase shifts of 60°, 180°, and 300° as shown in FIG. **6**. During the second operating mode when only the three coupled phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$ are active, the switching circuits $\mathbf{16}_1$, $\mathbf{16}_2$, and $\mathbf{16}_3$ switch the coupled phases at frequency F_{sw} and at relative phase shifts of 0°, 120°, and 240°. And during the first operating mode when only the uncoupled phase **14** is active, then the switching circuit **26** switches the uncoupled phase at frequency F_{sw}, or, alternatively, at 2·F_{sw} or 3·F_{sw}.

[0054] With the second switching technique, the ripple frequency of I_{out}, and thus the ripple frequency of V_{out}, approximately equals 2·NAC·F_{sw}. Also, in the third operating mode when all of the phases $\mathbf{12}_1$-$\mathbf{12}_3$ and **14** are active, the ripple amplitudes of I_{out} and V_{out} may be less than when the converter **60** operates according to the first embodiment of the switching technique.

[0055] Still referring to FIG. **6**, alternate embodiments of the second switching technique are contemplated. For example the phase **14** may be switched on at approximately the same times that the phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$ are switched on; in the embodiment of FIG. **6**, this may be accomplished by shifting PWM**4** by 60° relative to F_{sw}, which would reduce the frequency of the I_{out}/V_{out} ripple to 3·F_{sw}. Moreover, although the converter **60** of FIG. **4** includes only three coupled phases and one uncoupled phase, the second switching technique may be scaled for more or fewer than three coupled phases and for more than one uncoupled phase. Furthermore, the alternate embodiments discussed above in conjunction with FIGS. **2**, **3**, and **5** may also be applicable.

[0056] FIG. **7** is a timing diagram of the signals PWM**1**, PWM**2**, PWM**3**, and PWM**4** of FIG. **4**, the respective phase currents IL**1**, IL**2**, IL**3**, and IL**4** through the phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$, and **14** of FIG. **3**, and I_{out} while the converter **60** of FIG. **1** is operating in the above-described third mode and according to a third embodiment of a switching technique. These signals may not be drawn to scale, and PWM**1**, PWM**2**, PWM**3**, and PWM**4** may have different duty cycles and respectively drive the high-side transistors $\mathbf{22}_1$-$\mathbf{22}_3$ and **32**, respectively.

[0057] Referring to FIGS. **4** and **7**, the phase activator **38** of FIG. **4** implements the third embodiment of the switching technique by causing the switching circuits $\mathbf{16}_1$, $\mathbf{16}_2$, $\mathbf{16}_3$, and **26** to switch the phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$ at a frequency F_{sw} and at relative phase shifts of 360°/NAC, where NAC=number of active coupled phases, and by causing the switching circuit **26** to switch the uncoupled phase **14** at F_{sw} and at the same relative phase shift as one of the coupled phases. For example, during the third operating mode when all four phases $\mathbf{12}_1$, $\mathbf{12}_2$, $\mathbf{12}_3$, and **14** are active, the switching circuits $\mathbf{16}_1$, $\mathbf{16}_2$, $\mathbf{16}_3$, and **26** switch the phases $\mathbf{12}_1$-$\mathbf{12}_3$ at relative phase shifts of 0°, 120°, 240°and the phase **14** at a relative phase shift of 0° (the same relative phase shift as the phase $\mathbf{12}_1$) as shown in FIG. **7**. During the second operating mode when only the three coupled phases $\mathbf{12}_1$, $\mathbf{12}_2$, and $\mathbf{12}_3$ are active, then the switching circuits $\mathbf{16}_1$-$\mathbf{16}_3$ switch the coupled phases at frequency F_{sw} and at relative phase shifts of 0°, 120°, and 240°. And during the first operating mode when only the uncoupled phase **14** is active, the switching circuit **26** switches the uncoupled phase at frequency F_{sw}.

[0058] With the third switching technique, the ripple frequency of I_{out}, and thus the ripple frequency of V_{out}, approximately equals NAC·F_{sw}.

[0059] Still referring to FIG. **7**, alternate embodiments of the third switching technique are contemplated. For example, the third switching technique may be scaled for numbers of coupled phases greater than or less than three and for numbers of uncoupled phases greater than one. Furthermore, alternate embodiments described above in conjunction with FIGS. **2**, **3**, **5**, and **6** may be applicable.

[0060] FIG. **8** is an isometric view of an inductor assembly **70** that may include a common core **72** for the magnetically coupled windings **18** and the magnetically uncoupled winding **28** of the buck converters **10** and **60** of FIGS. **1** and **4**. For purposes of illustration, the assembly **70** is described as including the windings $\mathbf{18}_1$-$\mathbf{18}_3$ and **28** of the buck converter **60**. Including a common core for coupled and uncoupled windings may reduce the cost of, and the layout area occupied by, the windings as compared to using separate cores for the coupled and uncoupled windings.

[0061] The common core **72** includes magnetically coupled winding forms $\mathbf{74}_1$-$\mathbf{74}_3$, an optional leakage form **76**, a magnetically uncoupled winding form **78**, and members **80** and **82**, which interconnect the forms. That is, using a ladder analogy, the forms $\mathbf{74}_1$-$\mathbf{74}_3$, **76**, and **78** are the rungs of the ladder, and the members **80** and **82** are the rails to which the rungs are coupled. The member **80** includes an optional first gap **84** and a second gap **86**. And spaces $\mathbf{88}_1$-$\mathbf{88}_4$ separate the forms $\mathbf{74}_1$-$\mathbf{74}_3$, **76**, and **78**.

[0062] The forms $\mathbf{74}_1$-$\mathbf{74}_3$ may have the same cross-sectional dimensions and be made from the same material, for example, where the windings $\mathbf{18}_1$-$\mathbf{18}_3$ carry balanced portions of the output current I_{out}.

[0063] Alternatively the forms $\mathbf{74}_1$-$\mathbf{74}_3$ may have different dimensions or be made of different materials, for example, where the windings $\mathbf{18}_1$-$\mathbf{18}_3$ carry unbalanced currents as described in related U.S. patent application Ser. No. 12/136,018.

[0064] The first gap **84** and the leakage form **76** cooperate to allow a specified amount of leakage flux ϕ_{leak} to flow when a high-side switch **22** or **32** (FIG. **4**) couples a respective one of the windings $\mathbf{18}_1$-$\mathbf{18}_3$ is driven with the input voltage Vin (FIG. **4**). The gap **84** has a length I**1** and may be partially or fully filled with a material other than air, I**1** and the fill material depending on the specified leakage flux ϕ_{leak}. Likewise, the leakage form **76** has cross-sectional dimensions and is made from a material (which may be different from the material from which the forms **74** are made), the dimensions and material depending on the specified leakage flux ϕ_{leak}. The leakage flux ϕ_{leak} provides an effective filter inductance that the load **15** (FIG. **4**) "sees" when the phases $\mathbf{12}_1$- $\mathbf{12}_3$ are active and the phase **14** is inactive. U.S. patent application Ser. No. 11/903,185 discusses such leakage inductance in more detail.

[0065] The second gap **86** has a length I**2** (which may be longer or shorter than I**1**) and may be partially or fully filled with a material other than air to allow at most a negligible amount of flux to flow between any of the forms $\mathbf{74}_1$-$\mathbf{74}_3$ and the form **78**, where a "negligible amount" may be defined for the specific application. For example, the flux flowing from the form $\mathbf{74}_1$ to the form **78** via the gap **86** may be negligible if this flux is no more than 1.0% of the total flux ϕ_T induced in the form $\mathbf{74}_1$ by the current IL**1** flowing through the winding $\mathbf{18}_1$. Likewise, in this example, the flux flowing from the form **78** to the forms $\mathbf{74}_1$-$\mathbf{74}_3$ via the gap **86** may be negligible if this flux is no more than 1.0% of the flux induced in the form **78** by the current IL**4** (FIGS. **5**-**7**) through the winding **28**.

[0066] The dimensions and material of the form **78** may be selected to give the magnetically uncoupled winding **28** a specified inductance.

[0067] Each winding $\mathbf{18}_1$-$\mathbf{18}_3$ and **28** is formed from a respective conductor $\mathbf{90}_1$-$\mathbf{90}_3$ and **92**, which has a respective width W_1-W_4, is partially wound about a corresponding form $\mathbf{74}_1$-$\mathbf{74}_3$, and **78**, and extends beneath and adjacent to the remaining forms. For example, the winding $\mathbf{18}_1$ is formed from a conductor $\mathbf{90}_1$ that is partially wound about the form $\mathbf{74}_1$ and extends beneath and adjacent to the remaining forms $\mathbf{74}_2$-$\mathbf{74}_3$, **76**, and **78**. Similarly, the winding $\mathbf{18}_2$ is formed from a conductor $\mathbf{90}_2$ that is partially wound about the form $\mathbf{74}_2$ and extends beneath and adjacent to the remaining forms $\mathbf{74}_1$, $\mathbf{74}_3$, **76**, and **78**, and so on. The conductors $\mathbf{90}_1$-$\mathbf{90}_3$ and **92** may be made from any suitable conductive material such as copper or another metal, and may, but need not be, electrically insulated from the forms $\mathbf{74}_1$-$\mathbf{74}_3$, **76**, and **78**.

[0068] Furthermore, the implications of the conductors $\mathbf{90}_1$-$\mathbf{90}_3$ and **92** being partially wound about the respective forms $\mathbf{74}_1$-$\mathbf{74}_3$ and **78** are discussed in U.S. patent application Ser. No. 11/903,185, which is incorporated by reference.

[0069] Referring to FIGS. **4** and **8**, the operation of the inductor assembly **70** is described when a current IL**1** flows from V_{in}, trough the transistor $\mathbf{22}_1$, and through the winding $\mathbf{18}_1$ in the direction shown, it being understood that the operation is similar when a current flows through the other windings $\mathbf{18}_2$-$\mathbf{18}_3$. For purposes of example, it is assumed that the entire core **72** (the forms $\mathbf{74}_1$-$\mathbf{74}_3$, **76**, and **78** and the members **80** and **82**) is formed from the same magnetic material. It is also assumed that the forms $\mathbf{74}_1$-$\mathbf{74}_3$ have the same dimensions, and that the conductors $\mathbf{90}_1$-$\mathbf{90}_3$ and **92** have the same widths W. Furthermore, it is assumed that the forms $\mathbf{74}_2$-$\mathbf{74}_3$ do not pass inside the Faraday loop through which the current IL**1** flows. Moreover, it is assumed that the form **76** and the gap **84** are present.

[0070] As the current IL**1** flows through the winding $\mathbf{18}_1$, it generates a total magnetic flux ϕ_T, which, in a first-order approximation, flows through the form $\mathbf{74}_1$—in this approximation, flux flowing outside of the core **72** is presumed to be negligible, and is thus ignored.

[0071] A first portion ϕ_1 of the total flux ϕ_T flows through the form $\mathbf{74}_2$, a second portion ϕ_2 of the total flux ϕ_T flows through the form $\mathbf{74}_3$, and a third portion ϕ_{leak} flows through the leakage form **76** such that ϕ_T is given by the following equation:

$$\phi_T=\phi_1+\phi_2+\phi_{leak} \quad (1)$$

where $\phi_1=\phi_2$ because the forms $\mathbf{74}_2$ and $\mathbf{74}_3$ have the same dimensions and are made from the same material, and the reluctance of the portion of the members **80** and **82** between the forms $\mathbf{74}_2$ and $\mathbf{74}_3$ is assumed to be negligible.

[0072] The flux ϕ_1 induces a current IL**2** to flow through the transistor $\mathbf{24}_2$ and the winding $\mathbf{18}_2$, and the flux ϕ_2 induces a current IL**3** to flow through the transistor $\mathbf{24}_3$ and the winding $\mathbf{18}_3$.

[0073] Because the current IL**1** flowing in the winding $\mathbf{18}_1$ induces currents IL**2** and IL**3** in the windings $\mathbf{18}_2$ and $\mathbf{18}_3$, respectively, the windings $\mathbf{18}_1$-$\mathbf{18}_3$ are magnetically coupled to one another.

[0074] But the gap **86** has a reluctance large enough to allow no more than a negligible portion of ϕ_T to flow through the form **78**, and, therefore, the current IL**1** induces no more than a negligible current in the winding **28**.

[0075] Similarly, when a current IL**4** flows through the transistor **32** and the winding **28** and generates a flux through the form **78**, the gap **86** allows no more than a negligible portion of this flux to flow through the form $\mathbf{74}_1$, and, therefore, the current IL**4** through the winding **28** induces no more than a negligible current in the winding $\mathbf{18}_1$.

[0076] Consequently, because a current IL**1** through the winding $\mathbf{18}_1$ effectively induces no current in the winding **28**, and because a current driven through the winding **28** effectively induces no current in the winding $\mathbf{18}_1$, the winding $\mathbf{18}_1$ is magnetically uncoupled from the winding **28**. And because an analysis similar to the above analysis holds for the windings $\mathbf{18}_2$ and $\mathbf{18}_3$, the windings $\mathbf{18}_2$ and $\mathbf{18}_3$ are also magnetically uncoupled from the winding **28**.

[0077] Therefore, because the windings $\mathbf{18}_1$-$\mathbf{18}_3$ are magnetically coupled to one another but magnetically uncoupled from the winding **28**, the inductor assembly **70** is electrically equivalent to a first core having the windings $\mathbf{18}_1$-$\mathbf{18}_3$ and second core separate from the first core and having the winding **28**.

[0078] But as stated above, the inductor assembly **70** having the common core **72** may be smaller and otherwise less costly than an electrically equivalent multi-core inductor assembly.

[0079] Still referring to FIG. **8**, alternate embodiments of the inductor assembly **70** are contemplated. For example, although described as including three magnetically coupled windings and one magnetically uncoupled winding, the assembly **70** may be scaled to include more or fewer coupled windings and more uncoupled windings (an alternate embodiment with two coupled windings and one uncoupled winding may be suitable for use in the buck converter **10** of FIG. **1**). Furthermore, in some applications one may leave one or more of the windings **18** and **28** uncoupled. Moreover, the leakage form **76** and the gap **84** may be omitted. In addition, the conductors **90** and **92** may be wound about the respective

forms **74** and **78** any number of times. Furthermore, one or both of the gaps **84** and **86** may be disposed in the member **82** instead of in the member **80**. Moreover, the structure **70** may include multiple leakage forms. In addition, a gap similar to the gap **86** may be disposed on the other side of the form **78**, and the members **80** and **82** may be extended to accommodate one or more additional groups of magnetically coupled windings and leakage forms similar to the group including the windings $\mathbf{18}_1$-$\mathbf{18}_3$ (and forms $\mathbf{74}_1$-$\mathbf{74}_3$) and leakage form **76**, and to accommodate one or more additional uncoupled forms similar to the form **78**. Each of these additional groups of coupled windings may include more or fewer than three windings. An example of such an alternate embodiment is described below in conjunction with FIG. **13**; moreover, the inductor assembly **70** may be disposed within a package.

[0080] FIG. **9** is an isometric view of an inductor assembly **100** in which like numbers reference like components relative to the inductor assembly **70** of FIG. **8**.

[0081] The inductor assembly **100** may be similar to the inductor assembly **70** of FIG. **8**, except that the gap **84** is disposed in the form **76** instead of in the member **80**. Forming the gap **84** in the form **76** may increase the structural integrity of the assembly **100** as compared to that of the assembly **70**. And although not shown, the gap **86** may be disposed in the form **78**.

[0082] Alternate embodiments of the inductor assembly **100** are contemplated. For example, the alternate embodiments described above in conjunction with the inductor assembly **70** of FIG. **8** may be applicable to the assembly **100**.

[0083] FIG. **10** is an isometric view of an inductor assembly **110** in which like numbers reference like components relative to the inductor assembly **70** of FIG. **8**.

[0084] The inductor assembly **110** may be similar to the inductor assembly **70** of FIG. **8**, except that the leakage form **76** and the gap **84** are omitted and replaced with a leakage plate **112** (shown in transparent dashed line) that is disposed over and separated from the core **72**.

[0085] Therefore, the leakage flux ϕ_{Leak} flows through the plate **112** and the gap between the plate and the core **72**. The dimensions and material of the plate **112** may be selected to present a leakage-flux path having a specified reluctance to yield specified leakage inductances for the windings $\mathbf{18}_1$-$\mathbf{18}_3$, and to also provide a specified inductance for the winding **28** (a portion of the flux generated in the form **78** by the current IL**4** flowing through the winding **28** may flow through the plate **112**, thus affecting the inductance of the winding **28**).

[0086] An inductor assembly that includes a similar leakage plate is described in U.S. patent application Ser. No. 11/903,185, which is incorporated by reference.

[0087] Alternate embodiments of the inductor assembly **110** are contemplated. For example, the plate **112** may be sized so that it is not disposed over all of the forms **74** and **78**. For example, the plate **112** may not be disposed over the form **78** so as to have little or no affect on the inductance of the winding **28**. Furthermore, the dimensions and material of the plate **112**, and the spacing of the plate from the core **72**, may vary as a function of location so as to impart to each winding a flux leakage path having characteristics different from those of at least one other flux leakage path. Also, the assembly **110** may include a leakage form such as the leakage form **76** of FIG. **9** in addition to the leakage plate **112**. Moreover, the alternate embodiments described above in conjunction with the inductor assemblies **70** and **100** of FIGS. **8** and **9** may be applicable to the assembly **110**.

[0088] FIG. **11** is an isometric view of an inductor assembly **120** in which like numbers reference like components relative to the inductor assembly **70** of FIG. **8**.

[0089] The inductor assembly **120** may be similar to the inductor assembly **70** of FIG. **8**, except that the windings $\mathbf{18}_1$-$\mathbf{18}_3$ and **28** extend generally parallel to the forms $\mathbf{74}_1$-$\mathbf{74}_3$, **76**, and **78** instead of generally perpendicular to them, and the gap **86** is disposed in the form **78** instead of in the member **80**. A core similar to the core **72** of FIG. **11** is described in U.S. patent application Ser. No. 11/903,185, which is incorporated by reference.

[0090] Alternate embodiments of the inductor assembly **120** are contemplated. For example, the gap **84** may be disposed in the form **76** or in the member **82**, and the gap **86** may be disposed in the member **80** or the member **82**. Furthermore, a leakage plate similar to the leakage plate **112** of FIG. **10** may replace or be included in addition to the leakage form **76**. Moreover, the alternate embodiments described above in conjunction with the inductor assemblies **70**, **100**, and **110** of FIGS. **8**-**10** may be applicable to the assembly **120**.

[0091] FIG. **12** is an exploded isometric view of an inductor assembly **130** in which like numbers reference like components relative to the inductor assembly **70** of FIG. **8**.

[0092] The inductor assembly **130** may be similar to the inductor assembly **70** of FIG. **8**, except that members **80** and **82** may be wider and closer together, and the windings $\mathbf{18}_1$-$\mathbf{18}_3$ and **28** may extend generally in parallel with the forms $\mathbf{74}_1$-$\mathbf{74}_3$, **76**, and **78** and be wound about the forms in a plane that is generally parallel to the members **80** and **82**. For better viewing, the member **80** is shown exploded from the forms $\mathbf{74}_1$-$\mathbf{74}_3$, **76**, and **78** although the member **80** may be integral with these forms. A core similar to the core **72** of FIG. **12** is described in U.S. patent application Ser. No. 11/903,185, which is incorporated by reference.

[0093] Alternate embodiments of the inductor assembly **130** are contemplated. For example, a leakage plate similar to the leakage plate **112** of FIG. **10** may replace or be included in addition to the leakage form **76**. Moreover, the alternate embodiments described above in conjunction with the inductor assemblies **70**, **100**, **110**, and **120** of FIGS. **8**-**11** may be applicable to the assembly **130**.

[0094] FIG. **13** is an exploded isometric view of an inductor assembly **140** in which like numbers reference like components relative to the inductor assembly **70** of FIG. **8** and to the inductor assembly **130** of FIG. **12**.

[0095] The inductor assembly **140** may be similar to the inductor assembly **130** of FIG. **13**, except that the uncoupled winding **28** is omitted, and a second group of coupled windings $\mathbf{142}_1$-$\mathbf{142}_3$ are added and are respectively wound about forms $\mathbf{144}_1$-$\mathbf{144}_3$.

[0096] In an embodiment, a form **146** acts as a shared leakage form, and the gaps $\mathbf{148}_1$ and $\mathbf{148}_2$ magnetically isolate the first group of coupled windings $\mathbf{18}_1$-$\mathbf{18}_3$ from the second group of coupled windings $\mathbf{142}_1$-$\mathbf{142}_3$. For example, a current IL**1** driven through the winding $\mathbf{18}_1$ generates a total flux ϕ_{T1} and a leakage flux ϕ_{leak1}, which circulates through the gap $\mathbf{148}_1$ and the form **146**. However, the reluctance of the gap $\mathbf{148}_2$ allows no more than a negligible portion of the flux ϕ_{T1} to circulate through any one of the forms $\mathbf{144}_1$-$\mathbf{144}_3$. Similarly, a current IL**2** driven through the winding $\mathbf{142}_1$ generates a total flux ϕ_{T2} and a leakage flux ϕ_{leak2}, which circulates through the gap $\mathbf{148}_2$ and the form **146**. However, the reluctance of the gap $\mathbf{148}_1$ allows no more that a negligible portion of the flux ϕ_{T2} to circulate through any one of the forms

74_1-74_3. Alternatively, the form **146** may be replaced with two forms separated by a third gap. In this alternative, the leakage flux ϕ_{leak1} would circulate through the form closest to the first group of windings 18_1-18_3, and the leakage flux ϕ_{leak2} would circulate through the form closest to the second group of windings 142_1-142_2.

[0097] In another embodiment, the form **146** is omitted, and a single gap **148** magnetically isolates the first group of coupled windings 18_1-18_3 from the second group of coupled windings 142_1-142_3. One or more leakage plates similar to the plate **112** of FIG. **10** may be included in the assembly **140** to provide paths for leakage inductance. Or, respective leakage forms, one for each group of coupled windings, may be disposed remote from the single gap **148**.

[0098] In yet another embodiment, the gaps 148_1 and 148_2 may have respective reluctances large enough to allow no more than a negligible flux to flow through either gap and through the form **146**. Therefore, because in this embodiment the form **146** is magnetically isolated from the first and second groups of windings 18_1-18_3 and 142_1-142_3, a magnetically uncoupled winding may be wound about the form **146**.

[0099] Alternative embodiments of the inductor assembly **140** are contemplated. For example, the lengths of the members **80** and **82** may be extended to include more than two magnetically isolated groups of magnetically coupled windings, and to include more leakage forms and uncoupled windings. Furthermore, one or more leakage plates may be included, instead of or in addition to leakage forms. For example, a leakage plate may be included adjacent to one group of windings, and another group may include a leakage form. Or, a leakage plate may be adjacent to a group of coupled windings that also includes a leakage form. Also, a single leakage plate may be adjacent to more than one group of windings. Moreover, alternate embodiments described above in conjunction with the inductor assemblies **70**, **100**, **110**, **120**, and **130** of FIGS. **8**-**12** may be applicable to the assembly **140**.

[0100] FIG. **14** is a block diagram of a system **150** (here a computer system), which may incorporate a power supply (such as one of the buck converters **10** and **60** of FIGS. **1** and **4**) **152** that includes one or more of the inductor assemblies **70**, **100**, **110**, **120**, **130**, and **140** of FIGS. **8**-**13**.

[0101] The system **150** includes computer circuitry **154** for performing computer functions, such as executing software to perform desired calculations and tasks. The circuitry **154** typically includes a controller, processor, or one or more other integrated circuits (ICs) **156**, and the power supply **152**, which provides power to the IC(s) **156**. As discussed above in conjunction with FIGS. **1** and **4**, one or more of these ICs may provide a load signal to the power supply **152**, which may use this signal to activate a corresponding combination of CI and UI phases. One or more input devices **158**, such as a keyboard or a mouse, are coupled to the computer circuitry **154** and allow an operator (not shown) to manually input data thereto. One or more output devices **160** are coupled to the computer circuitry **154** to provide to the operator data generated by the computer circuitry. Examples of such output devices **160** include a printer and a video display unit. One or more data-storage devices **162** are coupled to the computer circuitry **154** to store data on or retrieve data from external storage media (not shown). Examples of the storage devices **162** and the corresponding storage media include drives that accept hard and floppy disks, tape cassettes, compact disk read-only memories (CD-ROMs), and digital-versatile disks (DVDs).

[0102] From the foregoing it will be appreciated that, although specific embodiments have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the present disclosure. Furthermore, where an alternative is disclosed for a particular embodiment, this alternative may also apply to other embodiments even if not specifically stated.

1. A power supply, comprising:
an input node configured to receive an input voltage;
an output node configured to provide a regulated output voltage;
an odd number of magnetically coupled phase paths each coupled between the input and output nodes;
a first magnetically uncoupled phase path coupled between the input and output nodes; and
a power-supply controller coupled to the phase paths and configured:
to activate each of the magnetically coupled phase paths at a first frequency; and
to activate the magnetically uncoupled phase path at a second frequency that is substantially equal to a product of the first frequency and the odd number.

2. The power supply of claim **1**, further comprising:
an inductor assembly including a core having members; and
wherein each of the magnetically coupled and uncoupled phase paths includes a single winding disposed about a respective one of the members.

3. A power supply, comprising:
an input node configured to receive an input voltage;
an output node configured to provide a regulated output voltage;
an odd number of magnetically coupled phase paths each coupled between the input and output nodes;
a first magnetically uncoupled phase path coupled between the input and output nodes; and
an inductor assembly including a core having
a group of first members that are magnetically coupled to one another, and
a second member that is magnetically isolated from the first members;
wherein each of the magnetically coupled phase paths includes a winding disposed about a respective one of the first members; and
wherein the magnetically uncoupled phase path includes a winding disposed about the second member.

4. The power supply of claim **3**, further comprising a second magnetically uncoupled phase path coupled between the input and output nodes.

5. A system, comprising:
a power supply, including
an input node configured to receive an input voltage,
an output node configured to provide a regulated output voltage,
an odd number of magnetically coupled phase paths each coupled between the input and output nodes, the odd number of magnetically coupled phase paths being magnetically coupled to each other,
a magnetically uncoupled phase path coupled between the input and output nodes, and
a power-supply controller coupled to and configured to activate each of the magnetically coupled phase paths at a first frequency and to activate the magnetically uncoupled phase path at a second frequency that is

approximately equal to a product of the first frequency and the odd number; and

a load coupled to the output node of the power supply.

6. The system of claim **5**, further comprising:

an integrated-circuit die; and

wherein the controller and the load are disposed on the die.

7. The system of claim **5**, further comprising:

first and second integrated-circuit dies;

wherein the controller is disposed on the first die; and

wherein the load is disposed on the second die.

8. The system of claim **5** wherein the load includes an integrated circuit.

9. The method of claim **10** wherein activating the magnetically coupled phase paths includes activating each one of the magnetically coupled phase paths at a phase offset from a respective other one of the magnetically coupled phase paths, the phase offset substantially equal to a quotient of a total number of the magnetically coupled phase paths and 360 degrees.

10. A method, comprising:

activating each of an odd number of magnetically coupled phase paths at respective first frequencies, the odd number of magnetically coupled phase paths being magnetically coupled to one another; and

activating a first magnetically uncoupled phase path at a second frequency that is substantially equal to a product of the first frequency and the odd number.

11. A method, comprising:

activating each of an odd number of magnetically coupled phase paths at respective first frequencies; and

activating a first magnetically uncoupled phase path a second frequency;

wherein the second frequency is substantially equal to a product of the first frequency and the odd number;

wherein activating the magnetically coupled phase paths includes activating each one of the magnetically coupled phase paths at a first phase offset from a respective other one of the magnetically coupled phase paths, the phase offset being substantially equal to a quotient of a total number of the magnetically coupled phase paths and 360 degrees; and

wherein activating the magnetically uncoupled phase path includes activating the magnetically uncoupled phase path at a second phase offset from each of the magnetically coupled phase paths, the second phase offset being substantially equal to one half of the first phase offset relative to the first frequency.

12. A method, comprising:

activating each of an odd number of magnetically coupled phase paths at respective first frequencies; and

activating a first magnetically uncoupled phase path a second frequency;

wherein the second frequency is substantially equal to a product of the first frequency and the odd number;

wherein activating the magnetically coupled phase paths includes activating each one of the magnetically coupled phase paths at a first phase offset from a respective other one of the magnetically coupled phase paths, the phase offset being substantially equal to a quotient of a total number of the magnetically coupled phase paths and 360 degrees; and

wherein activating the magnetically uncoupled phase path includes activating the magnetically uncoupled phase path at a second phase offset from each of the magnetically coupled phase paths, the second phase offset being substantially equal to 180 degrees relative to the second frequency.

13. The method of claim **12**, further comprising activating a second magnetically uncoupled phase path at the second frequency.

14. The power-supply controller of claim **18** wherein:

the first number equals one; and

the second number is greater than one.

15. The power-supply controller of claim **18** wherein the phase controller is configured:

to enable the first number of magnetically uncoupled phase paths in response to a magnitude of the output current being smaller than the first threshold level; and

to enable the second number of magnetically coupled phase paths in response to the magnitude of the output current being greater than the first threshold level.

16. The power-supply controller of claim **18** wherein the phase controller is configured to enable at least one magnetically uncoupled phase path in response to a magnitude of the output current being greater than the first threshold level.

17. The power-supply controller of claim **18** wherein the phase controller is configured to disable the second number of magnetically coupled phase paths in response to a magnitude of the output current being smaller than the first threshold level.

18. A power-supply controller, comprising:

a phase controller configured

to enable a first number of magnetically uncoupled phase paths in response to an output current having a first relationship to a first threshold level, and

to enable a second number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level; and

an output-current monitor coupled to the phase controller, configured to be coupled to the magnetically uncoupled and coupled phase paths, and configured to determine the output current; and

wherein the phase controller is further configured

to activate each of the enabled first number of the magnetically uncoupled phase paths at a first frequency; and

to activate each of the enabled second number of the magnetically coupled phase paths at a second frequency that is substantially equal to a quotient of the first frequency divided by the second number.

19. The power-supply controller of claim **18**, further comprising:

an inductor assembly including a core having members; and

wherein each of the magnetically coupled and uncoupled phase paths includes a winding disposed about a respective one of the members.

20. A power-supply controller, comprising:

a phase controller configured

to enable a first number of magnetically uncoupled phase paths in response to an output current having a first relationship to a first threshold level, and

to enable a second number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level;

an output-current monitor coupled to the phase controller, configured to be coupled to the magnetically uncoupled and coupled phase paths, and configured to determine the output current;

an inductor assembly including a core having

a group of first members that are magnetically coupled to one another, and

a group of second members that are each magnetically isolated from the first members and from the other second members;

wherein each of the magnetically coupled phase paths includes a winding disposed about a respective one of the first members; and

wherein each of the magnetically uncoupled phase paths includes a winding disposed about a respective one of the second members.

21. The power-supply controller of claim **20** wherein the output-current monitor is configured to determine a magnitude of the output current.

22. A power supply, comprising:

an input node configured to receive an input voltage;

an output node configured to receive an output current and to provide a regulated output voltage and a load current;

a first number of magnetically uncoupled phase paths coupled between the input and output nodes, each of the first number of phase paths configured, when active, to provide a respective portion of the output current;

a second number of magnetically coupled phase paths coupled between the input and output nodes, each of the second number of the phase paths configured, when active, to provide a respective portion of the output current; and

a power-supply controller coupled to the first number of the magnetically uncoupled phase paths and to the second number of the magnetically uncoupled phase paths, the power-supply controller including

a phase controller configured

to enable the first number of magnetically uncoupled phase paths in response to the output current having a first relationship to a first threshold level,

to activate the enabled first number of magnetically uncoupled phase paths at a first frequency,

to enable the second number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level, and

to activate the enabled second number of magnetically coupled phase paths at a second frequency that is approximately equal to quotient of the first frequency divided by the second number, and

an output-current monitor coupled to the phase controller and to the magnetically uncoupled and coupled phase paths, and configured to determine the output current.

23. A system, comprising:

a power supply, including

an input node configured to receive an input voltage,

an output node configured to receive an output current and to provide a regulated output voltage and a load current,

a first number of magnetically uncoupled phase paths coupled between the input and output nodes, each of the first number of phase paths configured, when active, to provide a respective portion of the output current,

a second number of magnetically coupled phase paths coupled between the input and output nodes, each of the second number of the phase paths configured, when active, to provide a respective portion of the output current, and

a power-supply controller coupled to the first number of the magnetically uncoupled phase paths and to the second number of the magnetically uncoupled phase paths, the power-supply controller including

a phase controller configured

to enable the first number of magnetically uncoupled phase paths in response to the output current having a first relationship to a first threshold level, and

to enable the second number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level, and

an output-current monitor coupled to the phase controller and to the magnetically uncoupled and coupled phase paths, and configured to determine the output current;

wherein the phase controller is further configured

to activate each of the enabled first number of the magnetically uncoupled phase paths at a first frequency; and

to activate each of the enabled second number of the magnetically coupled phase paths at a second frequency that is substantially equal to a quotient of the first frequency divided by the second number; and

a load coupled to the output node.

24. The system of claim **23**, further comprising:

an integrated-circuit die; and

wherein the power-supply controller and the load are disposed on the die.

25. The system of claim **23**, further comprising:

first and second integrated-circuit dies;

wherein the controller is disposed on the first die; and

wherein the load is disposed on the second die.

26. The system of claim **23** wherein the load includes an integrated circuit.

27. A method, comprising:

enabling a magnetically uncoupled phase path in response to an output current having a first relationship to a first threshold level;

enabling a number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level;

wherein enabling the uncoupled phase path in response to the output current having a first relationship to the first threshold level includes enabling the uncoupled phase path in response to a magnitude of the output current being less than the first threshold level;

disabling the coupled phase paths in response to the magnitude of the output current being less than the first threshold level;

wherein enabling the coupled phase paths in response to the output current having a second relationship to the first threshold level includes enabling the coupled phase

paths in response to the magnitude of the output current being greater than the first threshold level; and

enabling the uncoupled phase path in response to the magnitude of the output current being greater than the first threshold level.

28. A method, comprising:

enabling a magnetically uncoupled phase path in response to an output current having a first relationship to a first threshold level;

enabling a number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level;

wherein enabling the uncoupled phase path in response to the output current having a first relationship to the first threshold level includes enabling the uncoupled phase path in response to a magnitude of the output current being less than the first threshold level;

disabling the coupled phase paths in response to the magnitude of the output current being less than the first threshold level;

wherein enabling the coupled phase paths in response to the output current having the first relationship to the first threshold level includes enabling the coupled phase paths in response to the magnitude of the output current being greater than the first threshold level;

disabling the uncoupled phase path in response to the magnitude of the output current being greater than the first threshold level and less than a second threshold level; and

enabling the uncoupled phase path in response to the magnitude of the output current being greater than the second threshold level.

29. A method, comprising:

enabling a magnetically uncoupled phase path in response to an output current having a first relationship to a first threshold level;

enabling a number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level;

while the magnetically coupled phase paths are enabled, activating each of the magnetically coupled phase paths at a first frequency; and

while the magnetically uncoupled phase path is enabled, activating the uncoupled phase path at a second frequency that is substantially equal to a product of the first frequency and the number of magnetically coupled phases.

30. A method, comprising:

enabling a magnetically uncoupled phase path in response to an output current having a first relationship to a first threshold level;

enabling a number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level;

while the magnetically coupled phase paths are enabled, activating each of the magnetically coupled phase paths at a first frequency and at a first time offset relative to one of the other coupled phase paths; and

while the magnetically uncoupled phase path is enabled, activating the uncoupled phase path at a second frequency that is substantially equal to a product of the first frequency and the number of magnetically coupled phases and at a second time offset relative to each of the coupled phase paths.

31. A method, comprising:

enabling a magnetically uncoupled phase path in response to an output current having a first relationship to a first threshold level;

enabling a number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level;

while the magnetically coupled phase paths are enabled, activating each of the magnetically coupled phase paths at a first frequency and at a first time offset relative to one of the other coupled phase paths; and

while the magnetically uncoupled phase path is enabled, activating the uncoupled phase path at the first frequency and at the first time offset relative to one of the coupled phase paths.

32. A method, comprising:

enabling a magnetically uncoupled phase path in response to an output current having a first relationship to a first threshold level;

enabling a number of magnetically coupled phase paths in response to the output current having a second relationship to the first threshold level;

while the magnetically coupled phase paths are enabled, activating each of the magnetically coupled phase paths at a first frequency and at a first time offset relative to one of the other coupled phase paths; and

while the magnetically uncoupled phase path is enabled, activating the uncoupled phase path at the first frequency and substantially in phase with one of the coupled phase paths.

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