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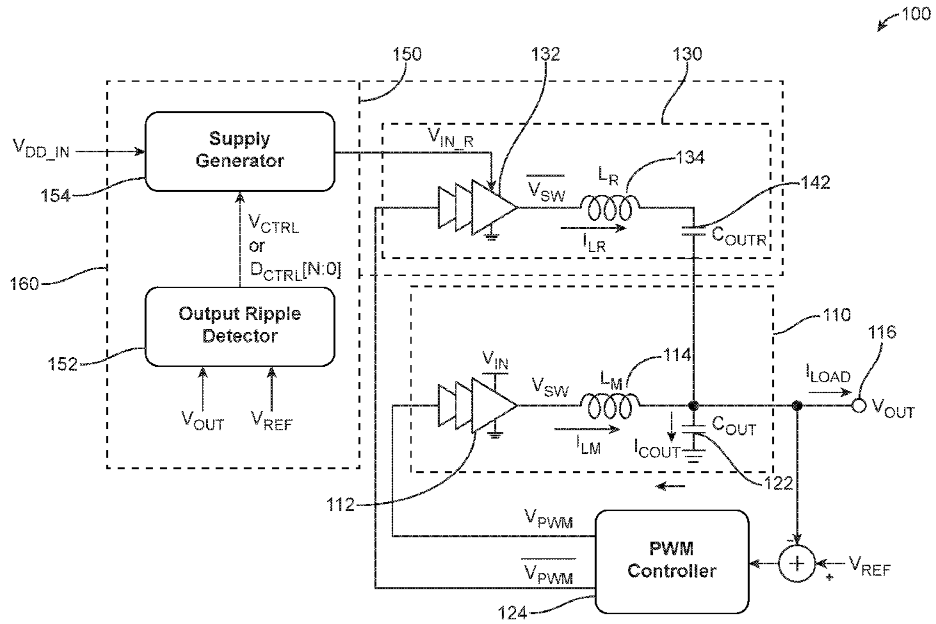

FIG. 2A

(57) **Abstract:** The present invention relates to circuitry and methods for ripple cancellation in switching voltage regulators. The ripple cancelling circuit 160 includes an inductor mismatch compensator circuit 150, a ripple cancellation circuit 130, and a pulse width modulation (PWM) controller 124. The method of ripple cancellation is based on detecting output ripple and varying supply voltage. The method uses a separate supply voltage for the cancellation path. The method involves a control technique to cancel mismatch between a ripple cancellation inductor 134 and the main inductor 114 in the circuit to achieve perfect ripple cancellation in the output voltage. Since inductor ripple current is proportional to input voltage, any mismatch between the inductors 114, 134 is corrected by increasing or decreasing the input supply voltage. The proposed method may be implemented in a multiphase DC-DC converter.

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RIPPLE CANCELLATION CIRCUIT IN SWITCHING DC-DC CONVERTERS AND METHODS THEREOF

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims priority to provisional patent application no. 201841033931 entitled Method of Ripple Cancellation in Switching DC-DC Converters filed on 10.09.2018.

FIELD OF THE INVENTION

[0002] The disclosure relates generally to output compensation in voltage converters and in particular to ripple current cancellation in switching DC-DC converters.

DESCRIPTION OF THE RELATED ART

[0003] A switching regulator suffers from large output ripple which makes it unsuitable for noise sensitive applications such as analog and RF. Prior techniques used to reduce the output ripple include increasing switching frequency, using large output capacitors or active ripple cancellation. Increasing switching frequency reduces overall efficiency, larger capacitor increase area and increases cost of the module. Also, conventional ripple cancellation techniques use parallel inductive path as shown in FIG. 1A which is 180 degree out of phase and ac coupled to inject equal and opposite ripple current. However, this technique requires perfect matching between main inductor and ripple cancellation inductor. Since inductors may easily have 10-20% tolerances, large mismatch between two inductors may result in negligible or no reduction in the output ripple. The mismatch between two inductors is due to manufacturing tolerances as well as dc current mismatch. Hence reduction in the output ripple could be as low as -0.5 which makes the ripple cancellation completely ineffective and -100% ripple is observed in the output voltage. The mismatch between the two inductors ripple cancellation inductor (L_R) and main inductor (L_M) is such that $L_R = (1 + k) \cdot L_M$ where k is the mismatch factor. k could be either negative of positive depending upon mismatch between L_R and L_M. Normalized ripple vs mismatch factor is shown in FIG. 1B. It can be concluded from FIG. 1B that k must be 0 for perfect ripple cancellation. Therefore a control technique to cancel the effect of mismatch between two inductors and thereby achieve perfect ripple cancellation in the output voltage is essential.

[0004] The US patent US8169201B2 discloses an output compensator for a regulator that can improve the dynamic response of the regulator. US7471155B1 describes a ripple cancellation circuitry that is used with a switching power supply that provides direct current (DC) power via a DC power amplifier (PA) signal to an RF PA final stage. A ripple cancellation converter having a high power factor is disclosed in the US patent US20170099710A1. ”A Passive Filter Building Block for Input or Output Current Ripple Cancellation in a Power Converter,” Soumya et al (IEEE Journal of Emerging and Selected Topics in Power Electronics, October, 2015) analyzes a coupled inductor based LL-LC network as a building block to achieve input or output current ripple cancellation in power converters.

[0005] System and methods are disclosed that may cancel the ripples in the output signal in a switching voltage regulator circuit.

SUMMARY OF THE INVENTION

[0006] In various embodiments a ripple cancelling circuit for generating a ripple cancelling current signal to cancel ripples in an output signal in a voltage regulator is disclosed. The compensator circuit includes an inductor mismatch compensator circuit and a ripple cancellation circuit. The inductor mismatch compensator circuit includes a ripple detector and a supply generator. The ripple detector is configured to receive the output signal from the voltage regulator and generate a control signal based on a difference between a reference signal and the received output signal. In various embodiments the supply generator is configured to receive the control signal and generate a supply signal. The ripple cancellation current signal generator circuit includes a voltage generator and a ripple cancellation inductor. The voltage generator is configured to receive the supply signal and a first pulse width modulated signal and generate a switching voltage signal. In various embodiments the ripple cancellation inductor is configured to receive the switching voltage signal and generate the ripple cancelling current signal.

[0007] In various embodiments the ripple cancelling circuit further includes a controller that is configured to receive the output signal and generate a first pulse width modulated signal and a second pulse width modulated signal. In various embodiments the first pulse width modulated signal and the second pulse width modulated signal are equal in magnitude and 180^{o} out of phase with each other.

[0008] In some embodiments the controller includes a first set of components that generate an inverted duty cycle control signal and a second set of components that generate signals that add to the inverted duty cycle control signal to produce the first pulse width modulated signal during a load/line transient. In some embodiments the first set of components comprise one or more of low pass filter, proportional integral derivative (PID) compensator or proportional integral (PI) compensator and the second set of components include one or more of high pass filter, proportional compensator or derivative compensator.

[0009] In various embodiments the ripple cancelling current signal is equal in magnitude and opposite in phase to a main inductor current signal produced at the voltage regulator. In various embodiments the supply signal is a function of the output signal.

[0010] In various embodiments a switching voltage regulator is disclosed. The switching voltage regulator includes a voltage conversion circuit that is configured to produce an output signal and a ripple cancelling circuit configured to generate a ripple cancelling current signal to cancel ripples in the output signal in the voltage regulator. In various embodiments the voltage conversion circuit includes an input voltage source and a first inductor producing a main inductor current signal. In various embodiments the ripple cancelling circuit includes an inductor mismatch compensator circuit and a ripple cancellation current signal generator circuit. In various embodiments the inductor mismatch compensator circuit includes a ripple detector that is configured to receive the output signal from the voltage regulator and generate a control signal based on a difference between a reference signal and the received output signal. In various embodiments the inductor mismatch compensator circuit further includes a supply generator that is configured to receive the control signal and generate a supply signal. In various embodiments the ripple cancellation current signal generator circuit includes a voltage generator and a ripple cancellation inductor. The voltage generator is configured to receive the supply signal and a first pulse width modulated signal and generate a switching voltage signal. The ripple cancellation inductor is configured to receive the compensating voltage signal and generate the ripple cancelling current signal.

[0011] In various embodiments the regulator includes a controller that is configured to receive the output signal and generate a first pulse width modulated signal and a second pulse width modulated signal. In various embodiments the first pulse width modulated signal and the second pulse width modulated signal are equal in magnitude and 180^{o} out of phase with each other. In various embodiments the first pulse width modulated signal is an input signal to the input voltage source. In various embodiments the second pulse width modulated signal is an input signal to the voltage generator.

[0012] In various embodiments the compensating current signal is equal in magnitude and opposite in phase to a main inductor current signal produced at the voltage regulator. In various embodiments the supply signal is a function of the output signal. In some embodiments the size of the ripple cancellation inductor is equal to the size of the first inductor or is smaller by a factor N, when the supply signal V_{IN_R} is scaled by a factor of N with respect to an input voltage V_{IN} of the input voltage source.

[0013] A method of cancelling ripples in an output signal of a switching voltage regulator is disclosed in some embodiments. The switching voltage regulator has a conversion circuit and a ripple cancelling circuit. The method includes the steps of receiving the output signal from the voltage regulator by a ripple detector. A control signal is generated by the ripple detector based on a difference between a reference signal and the received output signal. In various embodiments the control signal is received by a supply generator and generates a supply signal. A switching voltage signal is generated by a voltage generator that receives the supply signal and a first pulse width modulated signal. In various embodiments a ripple cancelling current signal is generated at a ripple cancellation inductor. In various embodiments the ripple cancelling current signal is equal in magnitude and opposite in phase to a main inductor current signal in the conversion circuit and in various embodiments, results in cancelling the ripples at the output signal at the load. In various embodiments the supply signal varies based on the output signal.

[0014] In some embodiments the first pulse width modulated signal is an inverted duty cycle voltage signal generated by a controller. In some embodiments the first pulse width modulated signal during a load/line transient is generated by the controller that has a first set of components that generate an inverted duty cycle control signal and a second set of components that generate signals that add to the inverted duty cycle control signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1A illustrates a conventional ripple cancellation circuit and corresponding waveforms.

[0016] FIG. 1B illustrates the normalized ripple vs mismatch factor in the prior art.

[0017] FIG. 2A shows the architecture level block diagram of the proposed voltage regulator with ripple cancellation circuitry.

[0018] FIG. 2B illustrates the proposed ripple cancellation circuitry having a smaller inductor in the ripple cancellation current signal generator circuit.

[0019] FIG. 2C illustrates the controller circuit for transient improvement.

[0020] FIG. 2D shows the improved transient response with ripple cancellation.

[0021] FIG. 3 illustrates the ripple cancellation technique.

[0022] FIG. 4 shows a plot of the normalized ripple vs. mismatch factor k with varying supply signal for the ripple cancellation method.

DETAILED DESCRIPTION

[0023] While the invention has been disclosed with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt to a particular situation or material to the teachings of the invention without departing from its scope.

[0024] Throughout the specification and claims, the following terms take the meanings explicitly associated herein unless the context clearly dictates otherwise. The meaning of "a", "an", and "the" include plural references. The meaning of "in" includes "in" and "on." Referring to the drawings, like numbers indicate like parts throughout the views. Additionally, a reference to the singular includes a reference to the plural unless otherwise stated or inconsistent with the disclosure herein.

[0025] The invention in its various embodiments relates to a ripple cancelling circuitry and methods for generating a ripple cancelling current signal that may cancel ripples in an output signal in a voltage regulator. The ripple cancelling circuitry includes an inductor mismatch compensator circuit and a ripple cancellation current signal generator circuit. The inductor mismatch compensator circuit is configured to receive output signal from the voltage regulator continuously or periodically and generate a varying supply voltage. The ripple cancellation circuit receives the varying supply voltage and produces a ripple cancelling current signal that is equal in magnitude and 180° out of phase with the current signal produced by an inductor in a voltage conversion circuit of the voltage regulator to cancel the ripples produced in the output signal. A switching voltage regulator incorporating the ripple cancelling circuitry is also disclosed. Further, a method of cancelling ripples in an output signal of a switching voltage regulator is also disclosed.

[0026] In various embodiments the invention includes a ripple cancelling circuit **160** for a voltage regulator that may cancel ripples or noises in the output signal V_{OUT}. The ripple cancelling circuit **160** produces a ripple cancelling current I_{LR} that may cancel the current signal I_{LM} produced in a main inductor **114** of the voltage regulator. In various embodiments the ripple cancelling circuit **160** as shown in FIG. 2A includes an inductor mismatch compensator circuit **150** and a ripple cancellation current signal generator circuit **130**. The inductor mismatch compensator circuit **150** includes a ripple detector **152** and a supply generator **154**. The ripple detector **152** receives the output voltage signal V_{OUT} from the output terminal **116** of the voltage regulator. The output voltage signal V_{OUT} that is received is compared with a reference voltage V_{REF} that is set in the inductor mismatch compensator circuit **150**. In various embodiments the ripple detector **152** generates a control signal V_{CTRL} that is a function of the difference between the set reference voltage V_{REF} and output signal V_{OUT}. In various embodiments the supply generator **154** is configured to receive the control signal produced at the ripple detector **152** and generate a supply signal V_{IN_R}. In various embodiments the supply signal V_{IN_R} is a function of the output signal V_{OUT} and varies as the output signal V_{OUT} changes.

[0027] In various embodiments the ripple cancellation current signal generator circuit **130** includes a voltage generator **132** and a ripple cancellation inductor **134**. The voltage generator **132** is configured to receive the supply signal V_{IN_R} from the supply generator **154** and a pulse width modulated signal $\overline{V_{PWM}}$ from a controller **124** to produce a switching voltage signal $\overline{V_{SW}}$. In various embodiments the ripple cancellation inductor **134** receives the switching voltage signal V_{IN_R} and produces a ripple cancelling current signal I_{LR}. In various embodiments the ripple cancelling current signal I_{LR} varies as the supply voltage V_{IN_R} changes. In various embodiments the magnitude of the ripple cancelling current signal $|I_{LR}|$ is equal in magnitude and 180° out of phase to a main inductor current I_{LM} produced in a main inductor **114** in the voltage conversion circuit **110** of the voltage regulator. In various embodiments the ripple cancelling current signal I_{LR} is matched with the main inductor current I_{LM} to cancel the ripples in the output signal V_{OUT}. The ripples in the output signal are due to a mismatch between the inductor

134 in the ripple cancellation current signal generator circuit and the main inductor **114** in a voltage conversion circuit. In various embodiments the ripples in the output signal V_{OUT} are cancelled by adjusting the supply signal V_{IN_R} to produce a ripple cancelling current signal I_{LR} that is equal to the magnitude of the main inductor current I_{LM}.

[0028] In some embodiments the inductor mismatch compensator circuit **150** is configured to operate in a continuous mode of operation. In this mode of operation the ripple detector **152** continuously receives the output signal V_{OUT} from the voltage regulator.

[0029] In some embodiments the inductor mismatch compensator circuit **150** is configured to operate in a periodic mode of operation. In some embodiments in the periodic mode of operation the inductor mismatch compensator circuit **150** may be turned ON periodically to detect any mismatch in the main inductor and the ripple cancellation inductor **134.** In various embodiments when a mismatch is detected the supply generator is configured to generate the desired supply signal V_{IN_R}. In some embodiments portions of the inductor mismatch compensator circuit **150** are configured to be turned OFF for a predetermined OFF time when the desired supply signal V_{IN_R} is reached. The portions of the inductor mismatch compensator circuit **150** that are switched off may include the ripple detector **152** that generates control signal $V_{CTRL.}$ The control signal V_{CTRL} may in some embodiments be either stored in a capacitor, or as digital control code during the predetermined OFF time. In some embodiments the digital control code may be generated in the ripple detector **152.** The digital control code may be stored in a memory unit during the predetermined OFF time. In various embodiments the memory unit is part of the inductor mismatch compensator circuit **150.** In various embodiments the periodic mode of operation is configured to reduce power consumed by the ripple detector **152** and the supply generator **154**.

[0030] In some embodiments the ripple cancellation inductor L_R **134** may be an inductor of smaller size than the main inductor L_M. The size of the ripple cancellation inductor L_R **184** as shown in FIG. 2B may be L_M/N, where L_M is the size of the main inductor and N may be an integer or a fraction. In some embodiments the size of the ripple cancellation inductor L_R **184** is half the size of the main inductor. In some embodiments L_M and V_{IN_R} are configured to be adjusted proportionally to achieve ripple cancellation.

[0031] In some embodiments during load/line transient, the ripple cancellation current signal generator circuit **130** may include an in-phase high bandwidth (faster) component of the control signal of the PWM controller. In one embodiment the PWM controller **124** is configured to generate inverted duty cycle control signal, D'_{Ctrl} by filtering using a low pass filter (LPF) the main duty cycle control signal, D_{Ctrl} and inverting as shown in FIG. 2C. In another embodiment D_{Ctrl} is passed through a high pass filter (HPF) **196** and added to D'_{Ctrl} to improve the transient response. In some embodiments the steady state (average) duty cycle of ripple cancelling PWM signal, ($\overline{V_{PWM}}$) is controlled by slow signal from LPF **194** while any instantaneous changes in the duty cycle during transient are controlled by the fast signal generated from HPF **196**. The improved transient response along with ripple cancellation is shown in FIG. 2D. In some embodiments, for the generation of inverted duty cycle control signal, D'_{Ctrl} for ripple cancellation integral (slow) components from a PID or PI compensator are used and proportional, derivative (fast) components may be added to D'_{Ctrl} to generate inverted duty cycle ($\overline{V_{PWM}}$).

[0032] In various embodiments a switching voltage regulator **100** is disclosed. The switching voltage regulator **100** includes a voltage conversion circuit **110** and a ripple cancelling circuit **160**. The voltage conversion circuit here means a circuit that may convert a source of current or voltage from one voltage level to another. In various embodiments the voltage conversion circuit **110** includes an input voltage source **112** that may be an ac or a dc source and a main inductor **114** carrying a main inductor current signal I_{LM}. In various embodiments the voltage conversion circuit **110** is configured to produce an output voltage signal V_{OUT} that is at a different voltage level from the voltage source.

[0033] The switching voltage regulator **100** further includes a ripple cancelling circuit **160** that is configured to generate signals that may cancel the ripples present in the output signal V_{OUT} of the switching voltage regulator. In various embodiments the generated signal is a ripple cancelling current signal I_{LR} that is equal in magnitude to the main inductor current signal I_{LM}. In various embodiments the ripple cancelling circuit **160** includes an inductor mismatch compensator circuit **150** and a ripple cancellation current signal generator circuit **130**. In various embodiments the inductor mismatch compensator circuit **150** includes a ripple detector **152** and a supply generator **154** that generates a variable supply signal V_{IN_R} that is a function of the output signal V_{OUT} from the switching voltage regulator **100**. In various embodiments the ripple detector **152** receives the output signal V_{OUT} from the output terminal **116** of the switching voltage regulator **100** and generates a control signal V_{CTRL} that is a function of a difference between a set reference signal in the ripple detector **152** and the received output signal from the switching voltage regulator **100**. In various embodiments the ripple detector **152** detects the ripples that are present in the output signal V_{OUT}. In various embodiments the supply generator **154** is configured to receive the control signal V_{CTRL} from the ripple detector **152** and generate a supply signal V_{IN_R}. In various embodiments the ripple cancellation current signal generator circuit **130** includes a voltage generator **132** that receives the supply signal V_{IN_R} from the supply generator **154** and a first pulse width modulated signal $\overline{V_{PWM}}$ from a controller **124**.

[0034] In various embodiments the voltage generator **132** generates a switching voltage signal $\overline{V_{SW}}$. In various embodiments the ripple cancellation inductor **134** is configured to receive the switching voltage signal $\overline{V_{SW}}$ and generate the compensating current signal I_{LR} that proportionally changes as the supply signal V_{IN_R} changes. In various embodiments the compensating current signal I_{LR} is equal in magnitude and is 180^{o} out of phase with the main inductor current signal I_{LM}. In various embodiments the ripple cancellation current signal I_{LR} and the main inductor current signal I_{LM} cancels the ripples in the output signal V_{OUT}. In various embodiments the switching voltage regulator **100** generates an output voltage V_{OUT} that is free of ripples.

[0035] In various embodiments a method of cancelling ripples in an output signal of a switching voltage regulator as shown in FIG. 3 is disclosed. The method **200** in step **210** includes sending the output signal from the output terminal of the voltage regulator to a ripple cancelling circuit. The output signal is received by a ripple detector in an inductor mismatch compensator circuit present in the ripple cancelling circuit. The ripple detector detects the ripples present in the output signal. In step **220** the ripple detector generates a control signal that is based on a difference between a set reference signal in the ripple detector and the received output signal from the output terminal of the voltage regulator. In step **230** the control signal is received by a supply generator that generates a supply signal. In various embodiments the supply varies as a function of the output signal. A switching voltage signal is generated in step **240** by a voltage generator that receives the supply signal and a first pulse width modulated signal from a controller. In step **250** a ripple cancelling current signal is generated in a ripple cancellation inductor. In various embodiments the ripple cancelling current signal is equal in magnitude and opposite in phase to a main inductor current signal in the conversion circuit. In various embodiments the magnitude of the ripple cancelling current signal varies as the supply signal varies. In various embodiments the ripple cancelling current signal is made equal to the magnitude of the main inductor current to remove any mismatch between the ripple cancellation inductor and the main inductor.

[0036] In some embodiments the method may be operated in a continuous mode of operation or a periodic mode of operation. In some embodiments in the continuous mode of operation the ripple detector continuously receives the output signal V_{OUT} from the voltage regulator.

[0037] In some embodiments in the periodic mode of operation the inductor mismatch compensator circuit may be turned ON periodically to detect any mismatch in the main inductor and the ripple cancellation inductor. In various embodiments when a mismatch is detected the supply generator generates the desired supply signal V_{IN_R}. In some embodiments portions of the ripple detector that generates control signal V_{CTRL} in the compensator circuit is turned OFF for a predetermined OFF time when the desired supply signal V_{IN_R} is reached.. The control signal V_{CTRL} may in some embodiments be stored in a capacitor in the ripple detector during the predetermined OFF time. In some embodiments the control signal may be stored as a digital control code that is generated in the ripple detector. The digital control code may be stored in a memory unit in the inductor mismatch compensator circuit during the predetermined OFF time.

[0038] In various embodiments the method of ripple cancelation is based on detecting the ripples in the output signal V_{OUT} and varying the supply signal V_{IN_R}. In various embodiments since the ripple cancelling current signal I_{LR} is proportional to the supply signal V_{IN_R}, any mismatch between the ripple cancellation inductor and the main inductor is corrected by increasing or decreasing the supply signal V_{IN_R}. In an example if ripple cancellation inductor L_R is more than the main inductor L_M then ripple cancelling current signal I_{LR} is less than the main inductor current I_{LM} hence do not cancel perfectly. In such cases the current signal I_{LR} is increased by increasing supply signal V_{IN_R} to a value such that $|I_{LM}| = |I_{LR}|$ in order to achieve perfect ripple cancellation. In various embodiments $|I_{LM}| = |I_{LR}|$ may be implemented by detecting the output ripple in the output signal and varying supply signal V_{IN_R} accordingly. In various embodiments the output ripple detector adjusts supply signal V_{IN_R} and settles to a value for which output ripple becomes zero. In various embodiments V_{IN_R} may be adjusted through digital or analog control.

[0039] In various embodiments the ripple current for the proposed method is written as:

$$I_{RIPPLE} = V_{IN}.D.(1-D).\left(\frac{1}{L_M} - \frac{V_{IN\_R}}{V_{IN}}.\frac{1}{L_R}\right).T_{sw}......(1)$$

For perfect ripple cancellation, $I_{RIPPLE} = I_{COUT} = 0$, substituting in (1), we get:

$$V_{IN\_R} = \frac{L_R}{L_M} V_{IN} \ldots\ldots (2)$$

$$L_R = (1+k)\, L_M ....(3)$$

where k is the mismatch factor. Thus,

$$V_{IN\_R} = (1+k) \cdot V_{IN} ....(4)$$

[0040] In various embodiments the condition to achieve zero output ripple or perfect ripple cancellation follows equation (4). In an exemplary embodiment V_{IN_R} is varied based on k and tuned accurately by controlling the control signal V_{CTRL} of the supply generator using ripple detector. The ripple detector varies V_{CTRL} dynamically, which in turn adjusts V_{IN_R}, until no ripple is detected at V_{OUT}. In some embodiments $V_{IN\_R} = V_{IN}/N$ where N could be an integer or a fraction. The condition for zero ripple when substituting $V_{IN\_R} = V_{IN}/N$ in eqn (1) is:

$$L_R = \frac{L_M}{N} ......(5)$$

which indicates that if we scale the supply voltage of ripple cancellation path by a factor of N with respect to main path supply, V_{IN} then ripple cancellation inductor may be scaled by the factor of N as well as shown in FIG. 3. This property can be used to use smaller inductor for ripple cancellation path. This property reduces switching and conduction losses in ripple cancellation path as well. In an example, if main path supply, V_{IN}=5V and L_M = 1µH then using $V_{IN\_R} = V_{IN}/5$ = 5V/5=1V reduces the size of L_R to $L_M/5$ = 1µH/5 = 200nH. In some embodiments mismatch between the inductor values L_M/N and L_R after this scaling may be corrected by changing the supply voltage V_{IN_R}. In various supply signal V_{IN_R} is generated by using any of the known voltage regulators techniques such as linear, switched capacitor, inductive or their combinations. In some embodiments in a multi-voltage system, any of the existing supply voltage may also be utilized as V_{IN_R}.

[0041] In an exemplary embodiment V_{IN_R} is varied based on k and tuned accurately by controlling the control signal V_{CTRL} of the supply generator using ripple detector. The ripple detector varies V_{CTRL} dynamically, which in turn adjusts V_{IN_R}, until no ripple is detected at V_{OUT}. The plot of the normalized ripple vs mismatch factor for varying control signal V_{IN_R}/ V_{IN}, is shown in FIG. 4 that indicates that the output ripple remains zero for all values of k if V_{IN_R} is adjusted according to equation (4). In various embodiments the method may be implemented in a multiphase DC-DC converter.

[0042] The advantage of the invention is that the ripple cancellation path may be operated at low voltage resulting in low cost and lesser area high voltage converters. Also small inductors and low voltage devices may be used in the ripple cancellation path.

[0043] Although the detailed description contains many specifics, these should not be construed as limiting the scope of the invention but merely as illustrating different examples and aspects of the invention. It should be appreciated that the scope of the invention includes other embodiments not discussed herein. Various other modifications, changes and variations which will be apparent to those skilled in the art may be made in the arrangement, operation and details of the system and method of the present invention disclosed herein without departing from the spirit and scope of the invention as described here. While the invention has been disclosed with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt to a particular situation or material the teachings of the invention without departing from its scope.

WE CLAIM:

1. A ripple cancelling circuit (160) for generating a ripple cancelling current signal to cancel ripples in an output signal in a voltage regulator (100) comprising:

an inductor mismatch compensator circuit (150) comprising

a ripple detector (152) configured to receive the output signal from the voltage regulator (100) and generate a control signal based on a difference between a reference signal and the received output signal;

a supply generator (154) configured to receive the control signal and generate a supply signal; and

a ripple cancellation current signal generator circuit (130) comprising

a voltage generator (132) configured to receive the supply signal and a first pulse width modulated signal and generate a switching voltage signal; and

a ripple cancellation inductor (134) configured to receive the switching voltage signal and generate the ripple cancelling current signal.

2. The ripple cancelling circuit of claim 1, wherein the circuit comprises a controller (124) configured to receive the output signal and generate a first pulse width modulated signal and a second pulse width modulated signal wherein the first pulse width modulated signal and the second pulse width modulated signal are equal in magnitude and 180^0 out of phase with each other.

3. The ripple cancelling circuit of claim 2, wherein the controller comprises first set of components to generate an inverted duty cycle control signal and a second set of components to generate signals that add to the inverted duty cycle control signal to produce the first pulse width modulated signal during a load/line transient.

4. The ripple cancelling circuit of claim 3, wherein the first set of components comprise one or more of low pass filter, proportional integral derivative (PID) compensator or proportional integral (PI) compensator and the second set of components include one or more of high pass filter, proportional compensator or derivative compensator.

5. The ripple cancelling circuit of claim 1, wherein the ripple cancelling current signal is equal in magnitude and opposite in phase to a main inductor current signal produced at the voltage regulator.

6. The ripple cancelling circuit of claim 1, wherein the supply signal is a function of the output signal.

7. A switching voltage regulator (100) comprising:

a voltage conversion circuit (110) configured to produce an output signal wherein the circuit comprises an input voltage source (112) and a first inductor (114) producing a main inductor current signal;

a ripple cancelling circuit (160) configured to generate a ripple cancelling current signal to cancel ripples in the output signal in the voltage regulator wherein the ripple cancelling circuit comprises:

an inductor mismatch compensator circuit (150) comprising

a ripple detector (152) configured to receive the output signal from the voltage regulator (100) and generate a control signal based on a difference between a reference signal and the received output signal;

a supply generator (154) configured to receive the control signal and generate a supply signal; and

a ripple cancellation current signal generator circuit (130) comprising a voltage generator (132) configured to receive the supply signal and a first pulse width modulated signal and generate a switching voltage signal; and

a ripple cancellation inductor (134) configured to receive the compensating voltage signal and generate the ripple cancelling current signal.

8. The switching voltage regulator of claim 7, wherein the regulator comprises a controller (124) configured to receive the output signal and generate a first pulse width modulated signal and a second pulse width modulated signal wherein the first pulse width modulated signal and the second pulse width modulated signal are equal in magnitude and 180^0 out of phase with each other.

9. The switching voltage regulator of claim 8, wherein the first pulse width modulated signal is an input signal to the input voltage source (112).

10. The switching voltage regulator of claim 8, wherein the second pulse width modulated signal is an input signal to the voltage generator (132).

11. The switching voltage regulator of claim 7, wherein the ripple cancelling current signal is equal in magnitude and opposite in phase to a main inductor current signal produced at the voltage regulator.

12. The switching voltage regulator of claim 7, wherein the supply signal is a function of the output signal.

13. The switching voltage regulator of claim 7, wherein the size of the ripple cancellation inductor is equal to the size of the first inductor or is smaller by a factor N,

when the supply signal V_{IN_R} is scaled by a factor of N with respect to an input voltage V_{IN} of the input voltage source.

14. A method of cancelling ripples in an output signal of a switching voltage regulator having a conversion circuit and a ripple cancelling circuit comprising the steps of:

receiving the output signal from the voltage regulator by a ripple detector;

generating a control signal by the ripple detector based on a difference between a reference signal and the received output signal;

receiving the control signal by a supply generator and generating a supply signal;

generating a switching voltage signal by a voltage generator receiving the supply signal and a first pulse width modulated signal;

generating a ripple cancelling current signal at a ripple cancellation inductor wherein the ripple cancelling current signal is equal in magnitude and opposite in phase to a main inductor current signal in the conversion circuit; and

cancelling ripples at the output signal at the load.

15. The method of claim 14, wherein the supply signal varies based on the output signal.

16. The method of claim 14, wherein the first pulse width modulated signal is an inverted duty cycle voltage signal generated by a controller.

17. The method of claim 14, wherein the first pulse width modulated signal during a load/line transient is generated by the controller that has a first set of components to generate an inverted duty cycle control signal and a second set of components to generate signals that add to the inverted duty cycle control signal.

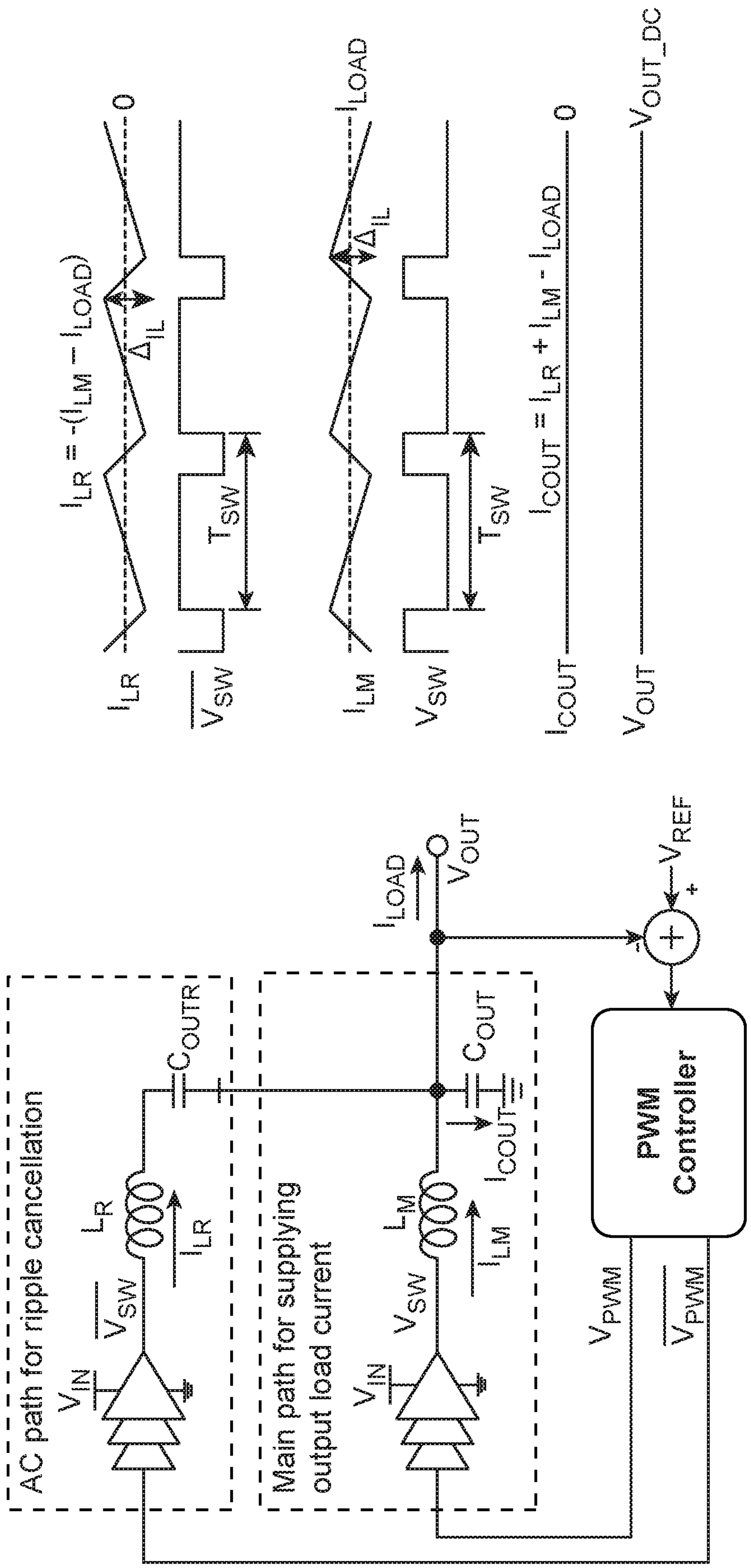


FIG. 1A
(PRIOR ART)

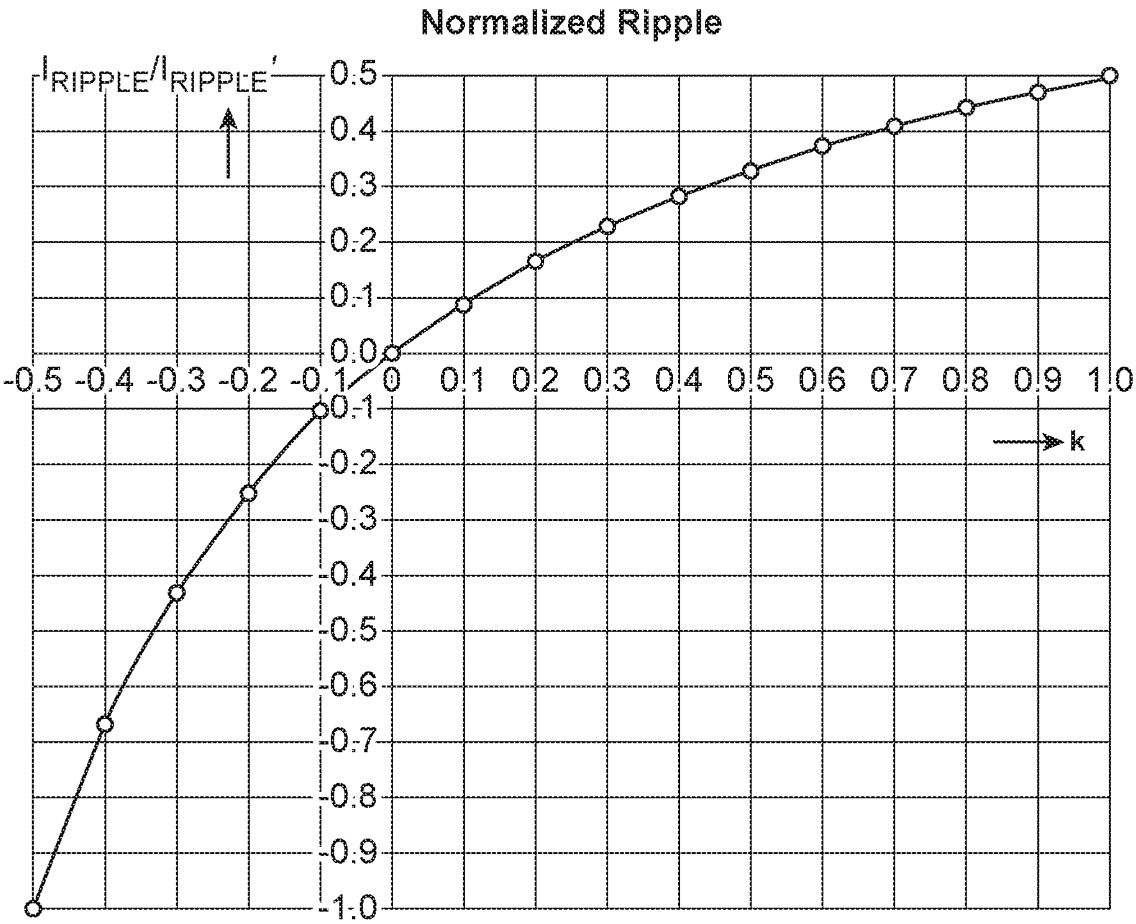


FIG. 1B
(PRIOR ART)

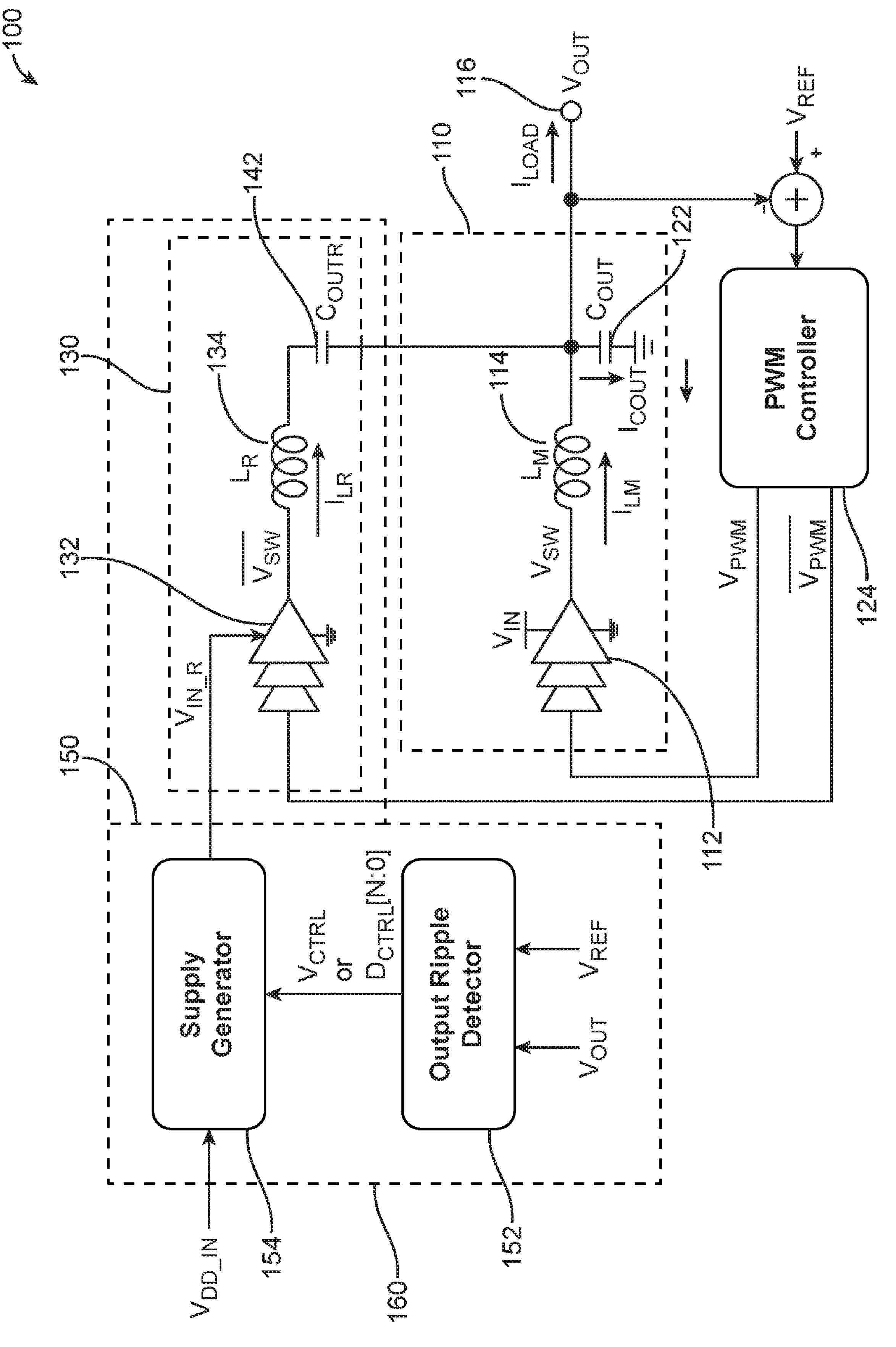
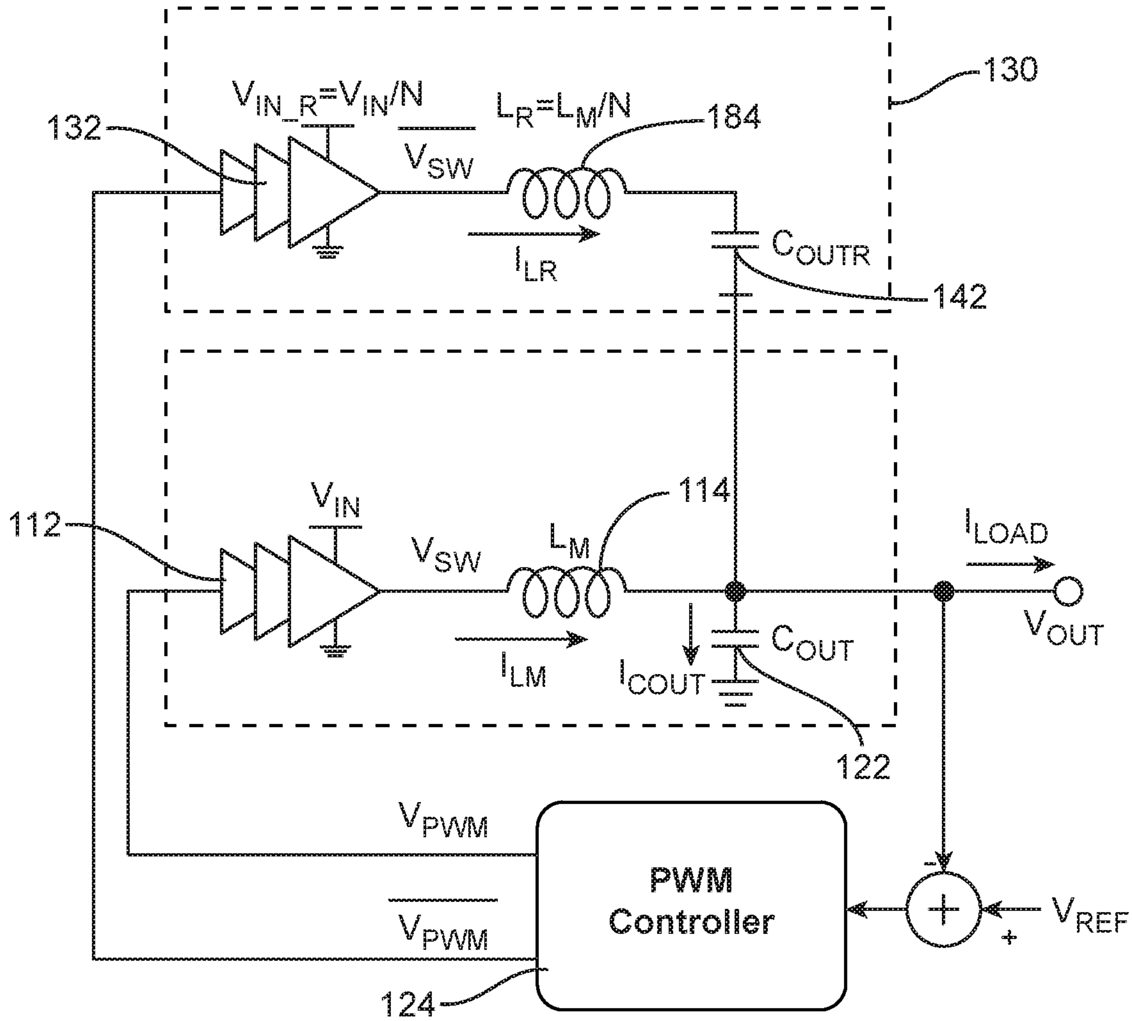

100
116
V_{OUT}
I_{LOAD}
V_{REF}
+
-
110
142
C_{OUTR}
122
C_{OUT}
130
134
L_R
I_{LR}
114
L_M
I_{LM}
I_{COUT}
PWM Controller
132
$\overline{V_{SW}}$
V_{SW}
V_{PWM}
$\overline{V_{PWM}}$
124
V_{IN_R}
V_{IN}
150
112
Supply Generator
V_{CTRL}
or
$D_{CTRL}[N:0]$
Output Ripple Detector
V_{REF}
V_{OUT}
V_{DD_IN}
154
152
160

FIG. 2A



130
132
$V_{IN\_R}=V_{IN}/N$
$\overline{V_{SW}}$
$L_R=L_M/N$
184
I_{LR}
C_{OUTR}
142
112
V_{IN}
V_{SW}
L_M
114
I_{LM}
I_{COUT}
C_{OUT}
122
I_{LOAD}
V_{OUT}
V_{PWM}
$\overline{V_{PWM}}$
PWM Controller
124
-
+
V_{REF}

FIG. 2B

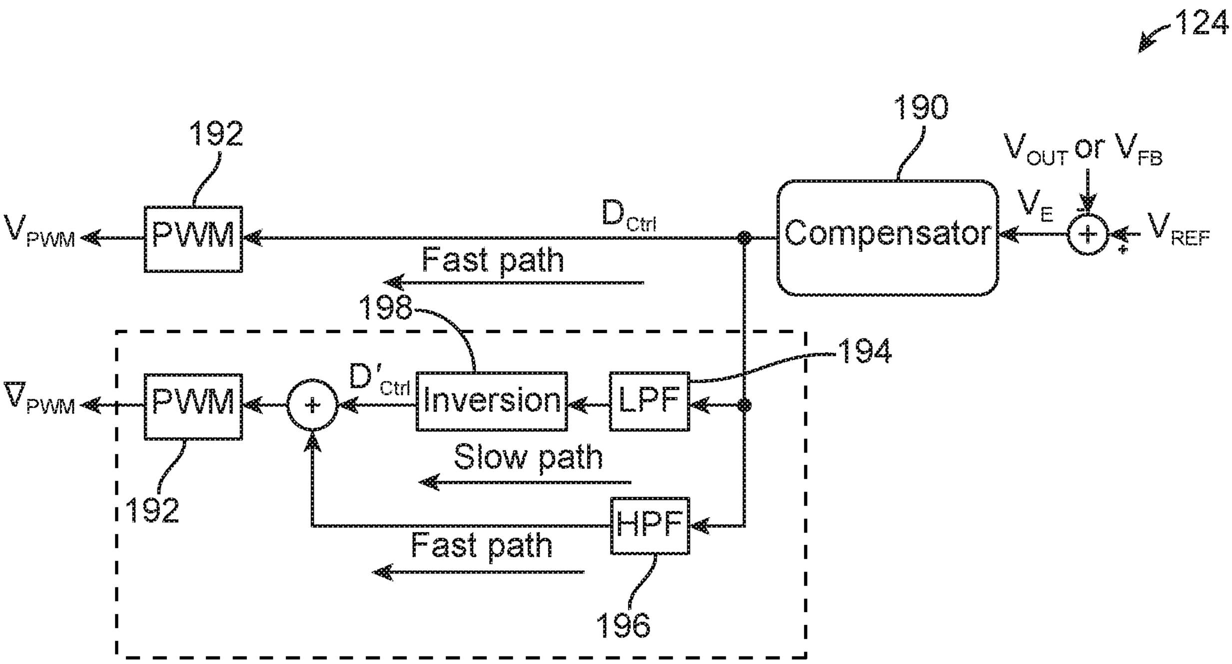

124
190
192
VOUT or VFB
VE
VREF
VPWM
PWM
DCtrl
Compensator
Fast path
198
194
D'Ctrl
Inversion
LPF
Slow path
HPF
Fast path
196

FIG. 2C

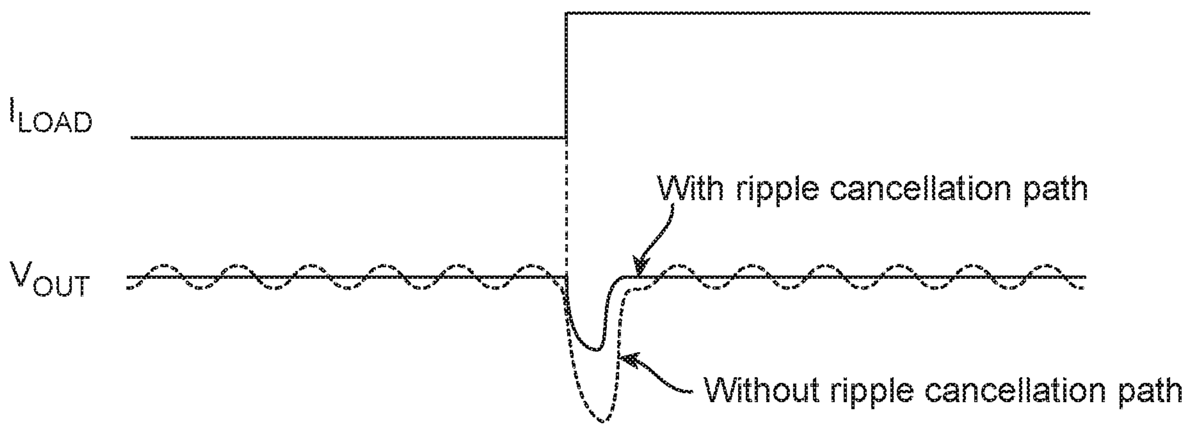

ILOAD
With ripple cancellation path
VOUT
Without ripple cancellation path

FIG. 2D

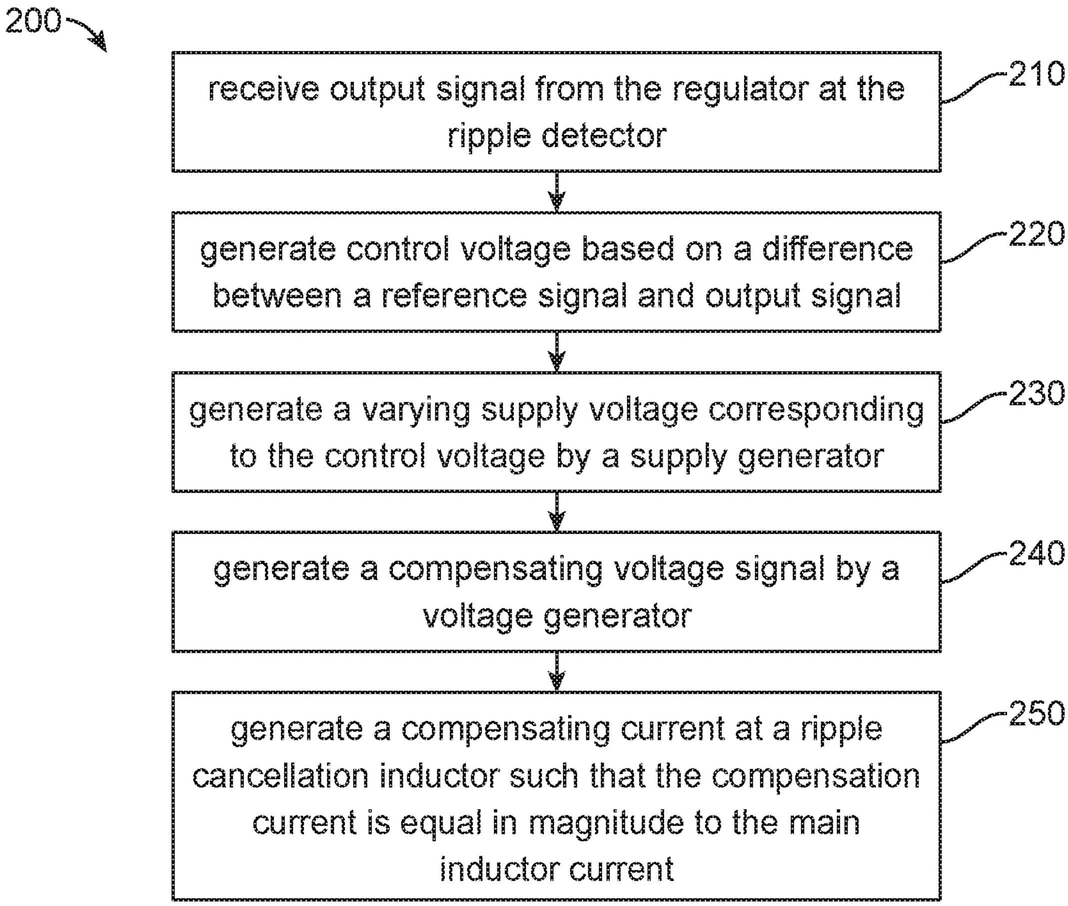

200
receive output signal from the regulator at the ripple detector
210
generate control voltage based on a difference between a reference signal and output signal
220
generate a varying supply voltage corresponding to the control voltage by a supply generator
230
generate a compensating voltage signal by a voltage generator
240
generate a compensating current at a ripple cancellation inductor such that the compensation current is equal in magnitude to the main inductor current
250

FIG. 3

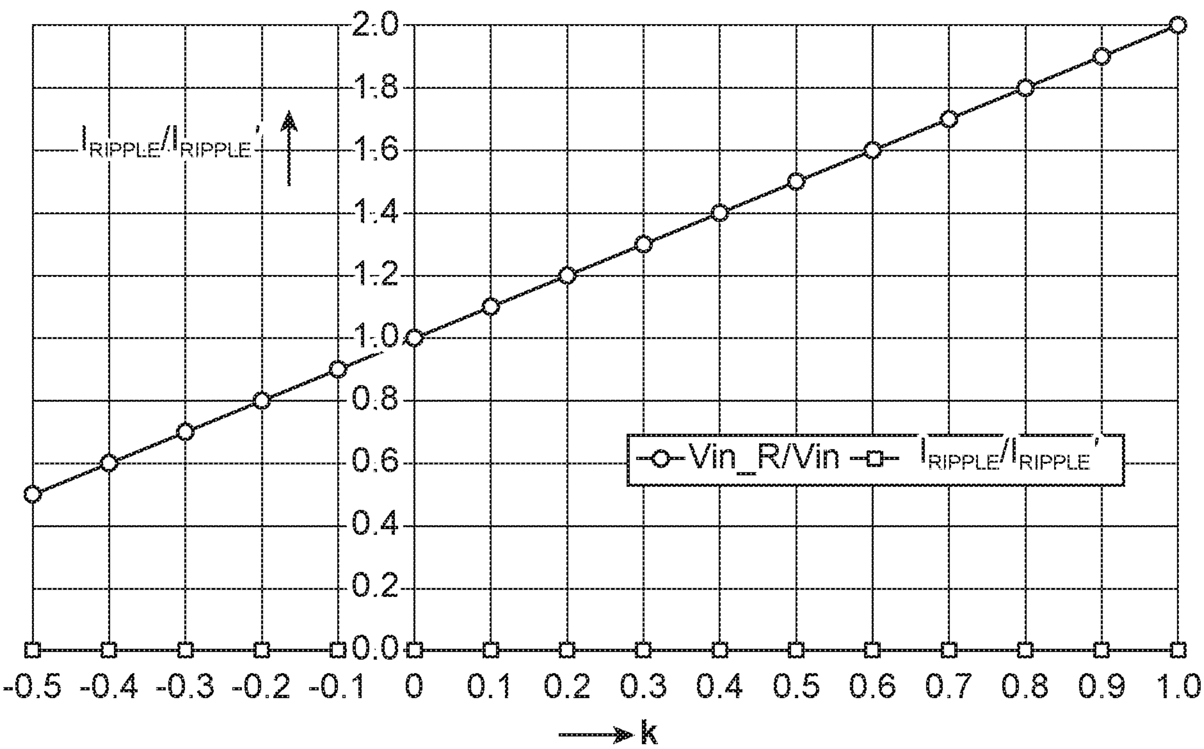

I_{RIPPLE}/I_{RIPPLE}'
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vin_R/Vin
I_{RIPPLE}/I_{RIPPLE}'
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
k

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IN2019/050656

A. CLASSIFICATION OF SUBJECT MATTER
H02M1/15,H02M1/08,H02M1/42,H02M3/156 Version=2019.01

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H02M

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

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

Databases: TotalPatent One, IPO Internal Database
Keywords: DC-DC converter, Ripple cancellation, Inductor mismatch

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 20150028832 A1 (GAZELLE SEMICONDUCTOR INC.); 29 January 2015 (29-01-2015), Whole document	1-17
X	US 7538535 B2 (DELL PRODUCTS LP); 26 May 2009 (26-05-2009), Whole document	1-17
A	US 20180183320 A1 (SYNAPTICS INCORPORATED); 28 June 2018 (28-06-2018), Figs. 2-3, 5; Paragraphs [0004]-[0005], [0010]-[0019], [0038]-[0047]	1-17

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "D" document cited by the applicant in the international application
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- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11-12-2019	11-12-2019

Name and mailing address of the ISA/	Authorized officer
Indian Patent Office Plot No.32, Sector 14,Dwarka,New Delhi-110075 Facsimile No.	Md. Tanveer Ur Rahman Telephone No. +91-1125300200

Citation	Pub.Date	Family	Pub.Date
US 20150028832 A1	29-01-2015	US 9577532 B2	21-02-2017
		WO 2015013032 A1	29-01-2015
		CN 105723600 A	29-06-2016
		TW 201516614 A	01-05-2015
US 7538535 B2	26-05-2009	US 2007165427 A1	19-07-2007
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		CN 110089027 A	02-08-2019
		WO 2018119465 A1	28-06-2018