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Buck Converter Continuous Conduction Operation

Abstract

Systems and methods described herein correspond to voltage regulator operations that enable voltage regulation even while an inductor current of the voltage regulator approaches or is at 0 amps (A). A voltage regulator may be operated in a three-level (3L) mode until a capacitor voltage is detected as out of regulation. The voltage regulator may be operated in a two-level (2L) mode to enable auxiliary circuitry to adjust the capacitor voltage back into regulation without adjusting a current supplied to a load. While the capacitor voltage is in regulation, the voltage regulator may operate in the 3L mode. The voltage regulator operations described herein enable continuous conduction operations near zero, which may reduce or eliminate a likelihood of switching harmonics being introduced as noise into power supplied from the voltage regulator.

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Background/Summary

BACKGROUND

[0001] This disclosure relates to systems and methods of power management circuitry of a semiconductor device and, more particularly, to power converters.

[0002] Integrated circuits are found in a vast array of electronics devices, including computers, handheld devices, wearable devices, vehicles, robotics, and more. An electronic device may be operated into various operational modes, such as a normal mode, a powered-off mode, and a reduced-power mode, among others. In some systems, circuit blocks designed to perform various functions may be designed to operate at different power supply levels. Power management circuitry may vary power supply levels delivered to the different circuit blocks.

[0003] Power management circuits sometimes include one or more power converter circuits that generate regulated voltage levels based on an input power supply signal. Such regulator circuits may employ different operations to regulate a respective voltage level. For example, a power converter may be buck converter, sometimes described as a step-down converter, or another suitable regulator. Yet operating these power circuits could result in switching harmonics being introduced into generated supply signals as noise. Noise in the supply signals may be difficult to filter out and/or may undesirably reduce accuracy downstream system operations based on the signals generated.

SUMMARY

[0004] Computer systems may include multiple circuits to perform specific operations. The circuits may be fabricated on one or more substrates and may use different power supply voltage levels. Power Management Units (PMUs) may include multiple power converter circuits that generate regulated voltage levels for various power supply signals delivered to one or more loads. Such power converter circuits may be designed to keep a voltage constant in view of changes in input voltage or circuit load. As part of this, the PMU may include or couple to power converters, like a buck converter, and rails, like a power rail.

[0005] The power converter circuits may regulate a voltage output based on load power consumption by maintaining the voltage output around a setpoint and varying output current to power the load. The power converter circuit, like a buck converter, may step down an input voltage to a lower, second voltage based on a flying capacitor (flycap) that acts like a floating power supply for the load. Should that load be operated to consume less power, the buck converter may respond by reducing an output current and maintaining the regulated voltage output at the second voltage based on charging or discharging the flycap.

[0006] A three-level (3L) buck converter may transmit a current waveform (e.g., inductor current) above 0 amps (A) or below 0 A—in other words, transmit the current waveform that has positive values with a minimum value being no lower than OA or negative values with a maximum value being no greater than 0 A—to enable suitable management of the charge of the flycap. This may be due to direction of the inductor current may become unpredictable or immeasurable around 0 A, or when the waveform has a zero-crossing. Indeed, the flycap may charge or discharge due to the current direction interacting unexpectedly with buck converter operations, as may happen if the buck converter is operated into a mode expected to charge the flycap and the current actually transmitted discharges the flycap. Unexpected charging or discharging of the flycap may lead to the load being supplied unregulated outputs, which may affect operation of the load (e.g., over current conditions). To cure this, control circuitry may operate the 3L buck converter according to discontinuous conduction operations that avoids transmitting the inductor current when within a threshold amount from 0 A.

[0007] To implement the discontinuous conduction operations, the control circuitry may operate an output of the buck converter into tristate to avoid transmitting the inductor current when within the threshold amount from OA. The output being in tristate stops the 3L buck converter from outputting the inductor current to the load. Although the discontinuous conduction operation stops transmission of unregulated power to the load, the discontinuous conduction operation increases a likelihood of switching harmonics being introduced into power supplies of the electronic device. Switching harmonics may introduce noise into supplied signals. Noise in the supplied signals may reduce reliability and/or be difficult to filter out. Thus, continuous conduction operations that are compatible with near OA inductor current generation (e.g., generation of an inductor current with a zero-crossing) may be desired.

[0008] Systems and methods described herein may enable the control circuitry to control the buck converter to generate an inductor current with zero-crossing as part of a continuous conduction operation. The buck converter may generate a relatively low amounts of power while operating in a continuous conduction operation, even when the generated voltage is regulated and the inductor current has a zero-crossing or is around zero. These systems and methods may improve buck converter operations by generating relatively small currents without increasing a likelihood of switching harmonics being introduced into power supplies.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Various aspects of this disclosure may be better understood upon reading the following detailed description and upon reference to the drawings described below.

[0010] FIG. **1** is a schematic block diagram of an electronic device, in accordance with an embodiment;

[0011] FIG. **2** is a front view of a mobile phone representing an example of the electronic device of FIG. **1**, in accordance with an embodiment;

[0012] FIG. **3** is a front view of a tablet device representing an example of the electronic device of FIG. **1**, in accordance with an embodiment;

[0013] FIG. **4** is a front view of a notebook computer representing an example of the electronic device of FIG. **1**, in accordance with an embodiment;

[0014] FIG. **5** are front and side views of a watch representing an example of the electronic device of FIG. **1**, in accordance with an embodiment;

[0015] FIG. **6** is a plot of a simulated current output from a buck converter operated by control circuitry in a discontinuous conduction operation, in accordance with an embodiment;

[0016] FIG. **7** is a plot of a simulated current output from the buck converter operated by control circuitry in a continuous conduction operation that permits zero-crossing, in accordance with an embodiment;

[0017] FIG. **8** is a block diagram of circuitry of the buck converter and control circuitry able to operate the buck converter in the continuous conduction operation that permits zero-crossing of FIG. **7**, in accordance with an embodiment;

[0018] FIG. **9**A is a circuit diagram of the buck converter of FIG. **8** in a first mode (“AB mode”), in accordance with an embodiment;

[0019] FIG. **9**B is a circuit diagram of the buck converter of FIG. **8** in a second mode (“AC mode”), in accordance with an embodiment;

[0020] FIG. **9**C is a circuit diagram of the buck converter of FIG. **8** in a third mode (“CD mode”), in accordance with an embodiment;

[0021] FIG. **9**D is a circuit diagram of the buck converter of FIG. **8** in a fourth mode (“BD mode”), in accordance with an embodiment;

[0022] FIG. **10** is a flowchart of a method performed by the control circuitry of FIG. **8** to operate the buck converter of FIG. **8** in the continuous conduction operation that permits zero-crossing of FIG. **7**, in accordance with an embodiment;

[0023] FIG. **11** is a diagrammatic representation of a state diagram of operations of the buck converter of FIG. **8** when being operated in the continuous conduction operation that permits zero-crossing of FIG. **7**, in accordance with an embodiment; and

[0024] FIG. **12** is a plot of a simulated voltage of a fly capacitor (flycap) of the buck converter of FIG. **8** while the buck converted is operated in the continuous conduction operation that permits zero-crossing of FIG. **7**, in accordance with an embodiment.

DETAILED DESCRIPTION

[0025] When introducing elements of various embodiments of the present disclosure, the articles “a,” “an,” and “the” are intended to mean that there are one or more of the elements. The terms “including” and “having” are intended to be inclusive and mean that there may be additional elements other than the listed elements. Additionally, it should be understood that references to “some embodiments,” “embodiments,” “one embodiment,” or “an embodiment” of the present disclosure are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features. Furthermore, the phrase A “based on” B is intended to mean that A is at least partially based on B. Moreover, the term “or” is intended to be inclusive (e.g., logical OR) and not exclusive (e.g., logical XOR). In other words, the phrase A “or” B is intended to mean A, B, or both A and B.

[0026] This disclosure relates to an electronic device that includes a power management unit (PMU). The electronic device **10** may be any suitable electronic device, such as a computer, a mobile phone, a portable media device, a tablet, a television, a virtual-reality headset, a wearable device such as a watch, a vehicle and/or vehicle dashboard, or the like. FIG. **1** is intended to represent one example of a particular implementation and is intended to illustrate the types of components that may be present in the electronic device **10**.

[0027] The electronic device **10** of FIG. **1** includes an electronic display **12**, one or more input devices **14**, one or more input/output (I/O) ports **16**, a processor core complex **18** having one or more processor(s) or processor cores, local memory **20**, a main memory storage device **22**, a network interface **24**, a power source **26** (e.g., power supply), and a power management unit (PMU) **28**. The various components described in FIG. **1** may include hardware elements (e.g., circuitry), software elements (e.g., a tangible, non-transitory computer-readable medium storing executable instructions), or a combination of both hardware and software elements. It should be noted that the various depicted components may be combined into fewer components or separated into additional components. For example, the local memory **20** and the main memory storage device **22** may be included in a single component.

[0028] The processor core complex **18** is operably coupled with local memory **20** and the main memory storage device **22**. Thus, the processor core complex **18** may execute instructions stored in local memory **20** or the main memory storage device **22** to perform operations, such as generating or transmitting image data to display on the electronic display **12**. As such, the processor core complex **18** may include one or more general purpose microprocessors, one or more application specific integrated circuits (ASICs), one or more field programmable gate arrays (FPGAs), or any combination thereof.

[0029] In addition to program instructions, the local memory **20** or the main memory storage device **22** may store data to be processed by the processor core complex **18**. Thus, the local memory **20** and/or the main memory storage device **22** may include one or more tangible, non-transitory, computer-readable media. For example, the local memory **20** may include random access memory (RAM) and the main memory storage device **22** may include read-only memory (ROM), rewritable non-volatile memory such as flash memory, hard drives, optical discs, or the like.

[0030] The network interface **24** may communicate data with another electronic device or a network. For example, the network interface **24** (e.g., a radio frequency system) may enable the electronic device **10** to communicatively couple to a personal area network (PAN), such as a Bluetooth network, a local area network (LAN), such as an 802.11x Wi-Fi network, or a wide area network (WAN), such as a 4G, Long-Term Evolution (LTE), or 5G cellular network. The power source **26** may provide electrical power to one or more components in the electronic device **10**, such as the processor core complex **18** or the electronic display **12**. Thus, the power source **26** may include any suitable source of energy, such as a rechargeable lithium polymer (Li-poly) battery or an alternating current (AC) power converter. One or more PMU(s) **28** may help distribute power to various circuitries of the electronic device **10**. Although multiple PMUs **28** may be described herein, for ease of description, these multiple PMUs **28** may sometimes be referred to herein as the PMU **28**. Some descriptions included herein may apply to systems with one PMU **28** and/or to systems with multiple PMUs **28**. Furthermore, PMUs **28** may include different components relative to each other, for example some PMUs **28** may include regulators while other PMUs **28** may not include regulators, as is described further herein. Some PMUs **28** may be themselves and/or couple to power one or more chip packages (e.g., as one or more loads). The chip package may include distinct die, powered by respective or the same buck converters, where one or more distinct die may be communicatively coupled to each other. The chip package of the PMU **28** may include one or more buck converters (e.g., one or more multi-level buck converter) for one or more of the respective distinct die.

[0031] The I/O ports **16** may enable the electronic device **10** to interface with other electronic devices. For example, when a portable storage device is connected, the I/O port **16** may enable the processor core complex **18** to communicate data with the portable storage device. The input devices **14** may enable user interaction with the electronic device **10**, for example, by receiving user inputs via a button, a keyboard, a mouse, a trackpad, a touch sensing, or the like. The input device **14** may include touch-sensing components (e.g., touch control circuitry, touch sensing circuitry) in the electronic display **12**. The touch-sensing components may receive user inputs by detecting occurrence or position of an object touching the surface of the electronic display **12**.

[0032] The electronic device **10** may take any suitable form. One example of the electronic device **10** in the form of a handheld device **10**A is shown in FIG. **2**. The handheld device **10**A may be a portable phone, a media player, a personal data organizer, a handheld game platform, or the like. For illustrative purposes, the handheld device **10**A may be a smartphone, such as any IPHONE® model available from Apple Inc.

[0033] The handheld device **10**A includes an enclosure **30** (e.g., housing). The enclosure **30** may protect interior components from physical damage or shield them from electromagnetic interference, such as by surrounding the electronic display **12**. The electronic display **12** may display a graphical user interface (GUI) **32** having an array of icons. When an icon **34** is selected either by an input device **14** or a touch-sensing component of the electronic display **12**, an application program may launch.

[0034] The input devices **14** may be accessed through openings in the enclosure **30**. The input devices **14** may enable a user to interact with the handheld device **10**A. For example, the input devices **14** may enable the user to activate or deactivate the handheld device **10**A, navigate a user interface to a home screen, navigate a user interface to a user-configurable application screen, activate a voice-recognition feature, provide volume control, or toggle between vibrate and ring modes.

[0035] Another example of a suitable electronic device **10**, specifically, a tablet device **10**B, is shown in FIG. **3**. The tablet device **10**B may be any IPAD® model available from Apple Inc. A further example of a suitable electronic device **10**, specifically a computer **10**C, is shown in FIG. **4**. For illustrative purposes, the computer **10**C may be any MACBOOK® or IMAC® model available from Apple Inc. Another example of a suitable electronic device **10**, specifically a watch **10**D, is shown in FIG. **5**. For illustrative purposes, the watch **10**D may be any APPLE WATCH® model available from Apple Inc. As depicted, the tablet device **10**B, the computer **10**C, and the watch **10**D each also includes an electronic display **12**, input devices **14**, I/O ports **16**, and an enclosure **30**. The electronic display **12** may display a GUI **32**. Here, the GUI **32** shows a visualization of a clock.

When the visualization is selected either by the input device **14** or a touch-sensing component of the electronic display **12**, an application program may launch, such as to transition the GUI **32** to presenting the icons **34** discussed in FIGS. **2** and **3**.

[0036] Referring back to FIG. **1**, circuitry of the electronic device **10**, such as those illustrated in FIG. **1**, may be fabricated on one or more substrates and may employ different power source **26** voltage levels. The PMU **28** may control and/or monitor signals delivering the electrical power from the power source **26**, which may be done based on one or more voltage regulator circuits that generate regulated voltage levels to be delivered to the various circuitries of the electronic device **10**. For example, the PMU **28** may adjust the electrical power delivered to one or more domains, such as an analog domain, a digital domain, or the like. The PMU **28** may adjust the voltage levels based on operational modes instructed by the processor core complex **18** and/or based on expected or desired energy consumption levels of one or more different components or systems of the electronic device **10**.

[0037] Such voltage regulator circuits may employ both passive circuit elements (e.g., inductors, capacitors) as well as active circuit elements (e.g., transistors, diodes). Different types of voltage regulator circuits may be employed based on power usage of load circuits, available circuit area, and the like. One type of voltage regulator circuit is a buck converter circuit (e.g., buck regulator), such as the buck converter depicted in FIGS. **8-9** and discussed herein.

[0038] Keeping the foregoing in mind, FIG. **6** is a plot **50** of a current **52** output simulated over time (t) from a buck converter operated by control circuitry in a discontinuous conduction operation. Although the current **52** output from the buck converter corresponds to the inductor current when the inductor current is transmitted from the buck converter, sometimes the current **52** transmitted from the buck converter differs in waveform from the inductor current, such as when the buck converter is operated to not output the inductor current (and thus the output current **52** goes to OA for a period of time).

[0039] In the discontinuous conduction operation, control circuitry stops the buck converter from outputting the current **52** when the inductor current of the buck converter drifts too close to 0 amps (A) or involves a zero-crossing. At and around OA, the direction (e.g., positive, negative) of the inductor current cannot be detected through reasonable methods able to be included in consumer electronics, if at all. To solve this uncertainty, when the inductor current is detected to be within a threshold from OA, the output of the buck converter may be operated into tristate to prevent the inductor current from being output. This corresponds to the gaps in transmissions of the current **52**. For example, in FIG. **6**, the buck converter for time periods t**1**, t**2**, and t**3** was simulated as being operated into tristate to block the inductor current **52** from being output. The discontinuous conduction operation helps prevent downstream over voltage conditions from arising based on unpredictable charging around the inductor current of OA. The discontinuous conduction operation may introduce switching harmonics, or noise. For example, the time periods t**1**, t**2**, and t**3** represent non-equal switching time periods that introduce switching harmonics into the supply of the inductor current.

[0040] Systems and methods described herein enable continuous conduction operation of the buck converter even while the inductor current drifts close to OA or involves a zero crossing. Doing so may prevent downstream over voltage conditions from arising while also reducing or eliminated introduced switching harmonics, which may increase a likelihood of reliable operation of downstream circuitry relative to discontinuous conduction operation of FIG. **6**.

[0041] To help illustrate, FIG. **7** is a plot **60** of a current **62** output simulated over time (t) from a buck converter operated by control circuitry in a continuous conduction operation that permits zero-crossing. Since the current **62** output is not stopped via tristate, the current **62** output corresponds to the inductor current of the buck converter.

[0042] The buck converter corresponding to the plot may be simulated to generate a current **62** that corresponds to an inductor current with a zero-crossing and averages overtime to a current value a threshold from OA (e.g., indicated via waveform average level **64** that is a relatively small positive value). Although the waveform average level **64** is shown here as a positive average current, it should be understood that a negative average current may be used. The relatively small average current may enable the buck converter to deliver relatively low amounts of power even while maintaining a regulated voltage output. The inductor current, through systems and methods described herein, may cross zero without its corresponding output (as current **62**) being stopped, enabling a reduction in switching harmonics introduced relative to discontinuous conduction operations.

[0043] Comparing FIGS. **6**-**7**, FIG. **7** includes the same marked periods t**1**, t**2**, and t**3**, where FIG. **7** shows the inductor current **62** as allowed to output and FIG. **6** shows the inductor current **52** as prevented from being output. FIG. **7** also includes designation of a 2-level (2L) mode and a 3-level (3L) mode. By switching between 2L modes and 3L modes as the inductor current **62** drifts to zero, the flycap charging and discharging is able to be controlled even if the direction of the inductor current **62** is unknown (or undetected), enabling more reliable downstream circuitry operation from less noisy supply control. Furthermore, the inductor current **62** output described with FIG. **7** may correspond to an inductor current generated by circuitry of FIG. **8**.

[0044] To elaborate, FIG. **8** is a block diagram of a system **70** of the electronic device **10**. The system **70** may include, in the PMU **28**, a buck converter **72** and auxiliary circuitry **74**. The system **70** may include control circuitry **76**. The control circuitry **76** may operate the buck converter **72** in the continuous conduction operation that permits zero-crossing of FIG. **7**.

[0045] The auxiliary circuitry **74** may include circuitry components that enable charging and/or discharging of the flycap **80**. The control of the auxiliary circuitry **74** may be based on control of a power bridge and a status of the flycap **80** voltage (e.g., sensed voltage value). In some systems, the auxiliary circuitry **74** may be considered an auxiliary interface, such as an additional portion of circuitry to enable the control circuitry **76** additional control over the buck converter **72**. The auxiliary circuitry **74** may include one or more active or passive components, such as one or more resistors, one or more transistors, one or more capacitors, one or more inductors, one or more switches, or the like.

[0046] The buck converter **72** may include four switches **78** (switch **78**A, switch **78**B, switch **78**C, switch **78**D). The switches **78** may be transistors or any suitable type of switch. Example transistors may include a field effect transistor (FET), a metal-oxide-semiconductor field-effect transistor (MOSFET), bipolar junction transistor (BJT), a junction-gate field-effect transistor (JFET), a PNP transistor, or any suitable transistor. It is noted that circuitry shown in FIG. **8** may be altered based on whether one or more switches **78** are of n-type or p-type.

[0047] The buck converter **72** may also include a flying capacitor, CF, (flycap) **80**. The flycap **80** may operate as a floating power supply used to regulate its output power. The buck converter **72** may transmit the inductor current and a voltage (V.sub.OUT) to power a load **84**. For example, the output voltage (V.sub.OUT) from the buck converter **72** may be regulated based on the charge of the flycap **80** that changes the flycap **80** voltage. When the flycap **80** is coupled to the inductor **82**, the inductor current may be based on the flycap **80** voltage.

[0048] The control circuitry **76** may use combinations of switch **78** to operate the buck converter **72** in a two-level (2L) mode or a 3L mode (e.g., “2L/3L” buck converter). The 2L mode and the 3L mode together may enable continuous conduction of current between the buck converter **72** and the load **84** at any inductor current (including at or near 0 A), as is described herein.

[0049] Different combinations of states of the switches **78** may change a direction of an inductor current through an inductor (Lx) **82**. Changing the direction of the inductor current may charge or discharge the flycap **80** based on the direction of the inductor current. The power output of the buck converter **72** may be regulated based on changing the charge of the flycap **80**, which regulates currents and voltages of nodes of the buck converter **72**. The switches **78** and the flycap **80** are may generate.

[0050] The control circuitry **76** may generate various control signals **86** to turn on and off pairs of the switches **78** to operate the buck converter **72** into various modes. Control signals **86** may be transmitted to one or more drivers **100** (driver **100**A, driver **100**B, driver **100**C, driver **100**D), which may pull up a voltage of the control signal **86** to a suitable voltage (e.g., V.sub.DD_A, V.sub.DD_B, V.sub.DD_C, V.sub.DD_D) to turn on or off a respective of the switches **78**A-D. The voltages, V.sub.DD_A, V.sub.DD_B, V.sub.DD_C, V.sub.DD_D, may be the same voltage or different voltages based on system design and/or material property differences between the respective of the switches **78**A-**78**D. Example modes of the various modes are illustrated in FIGS. **9**A-**9**D.

[0051] To elaborate, FIG. **9**A is a circuit diagram of the buck converter of FIG. **8** in a first mode ("AB mode"). FIG. **9**B is a circuit diagram of the buck converter of FIG. **8** in a second mode ("AC mode"). FIG. **9**C is a circuit diagram of the buck converter of FIG. **8** in a third mode ("CD mode"). FIG. **9**D is a circuit diagram of the buck converter of FIG. **8** in a fourth mode ("BD mode"). For ease of disclosure, FIGS. **9**A-**9**D are described together herein and generally referred to based on the different modes (e.g., AB mode, AC mode, CD mode, BD mode). It is noted that the inductor current **62** output described with FIG. **7** may correspond to the inductor current through the inductor **82** of FIG. **8**. As is elaborated on below, the AC mode may charge the flycap **80** and the BD mode may discharge the flycap **80**, where the charging or discharging being respectively based on the directionality of the inductor current. The AB mode and the CD mode may not charge or discharge the flycap **80** since the flycap **80** does not transmit the inductor current while in these modes.

[0052] In the AB mode, switches **78**A and **78**B may be closed and switches **78**C and **78**D may be open. In the AC mode, switches **78**A and **78**C may be closed and switches **78**B and **78**D may be open. In the CD mode, switches **78**C and **78**D may be closed and switches **78**A and **78**B may be open. In the BD mode, switches **78**B and **78**D may be closed and switches **78**A and **78**C may be open. In each of the different modes, the arrows illustrate an inductor current (ILX) generated via the buck converter **72** and transmitted from the inductor **82** as an output current. The various modes may correspond to switch **78** pairs, which when the switches **78** are transistors correspond to transistor pairs.

[0053] It is noted that in FIGS. **9**A-**9**D, the dashed arrow in each of the figures corresponds to positive current flow through the respective circuitry. The current flowing corresponds to the inductor **82** current. The inductor current can also flow in the opposite direction. When flowing in the opposite direction, the inductor current is a negative current.

[0054] In the AB mode of FIG. **9**A, the inductor current transmits from voltage supply (V.sub.IN) to the inductor **82** via switches **78**A and **78**B. The inductor current does not transmit through the flycap **80** based on the node CFM being in high impedance from the switches **78**C and **78**D being off. It is noted that node V.sub.LX is labelled as such in FIGS. **9**A-**9**D since a voltage of the node V.sub.LX corresponds to the voltage across the inductor **82**. Thus, the flycap **80** is not charged or discharged by the inductor current generated by the buck converter **72** while in the AB mode.

[0055] In the CD mode of FIG. **9**C, the inductor current transmits from voltage supply (V.sub.SS) to the inductor **82** via switches **78**C and **78**D. The inductor current does not transmit through the flycap **80** based on the node CFP being in a high impedance based on the switches **78**A and **78**B being off. Thus, the flycap **80** is not charged or discharged by the inductor current generated by the buck converter **72** while in the CD mode.

[0056] In the AC mode of FIG. **9**B, the inductor current transmits from voltage supply (V.sub.IN) to the inductor **82** via switches **78**A and **78**C. The inductor current transmits through the flycap **80** based on the nodes CFM and CFP having a low impedance path to the supply voltage and inductor voltage (e.g., node V.sub.LX). Thus, the flycap **80** is charged by the inductor current generated by the buck converter **72** when the inductor current is positive while in the AC mode. However, when the inductor current generated is negative in the AC mode, the flycap **80** is discharged.

[0057] In the BD mode of FIG. **9**D, the inductor current transmits from voltage supply (V.sub.IN) to the inductor **82** via switches **78**B and **78**D. The inductor current transmits through the flycap **80** based on the nodes CFM and CFP having a low impedance path to the ground and inductor voltage (e.g., node V.sub.LX). Thus, the flycap **80** is discharged by the inductor current generated by the buck converter **72** when the inductor current is positive while in the BD mode. However, when the inductor current generated is negative in the BD mode, the flycap **80** is charged.
[0058] In a 3L mode, the buck converter **72** may be operated to change two switch states (e.g., one switch opens and one switch closes). The control circuitry **76** may operate the buck converter **72** into the CD mode, then BD mode, then AB mode, then BC mode, and back to AC mode and repeat with the CD mode. In some cases, the control circuitry **76** is able to switch directly from CD mode to AB mode or vice versa and/or from BD mode to AC mode or vice versa. The control circuitry **76** may change to any of the mode states without first entering into an intermediate switch state. A 2L mode of the buck converter **72** may be based on the CD mode and the AB mode. Since the buck converter **72** can directly enter either of the CD mode or the AB mode from any of the 3L mode switch combinations (e.g., AB mode, AC mode, BD mode, CD mode), the control circuitry **76** may bypass an intermediate state when switching into the 2L mode from the 3L mode. This enables the control circuitry **76** to operate the buck converter **72** in the 2L mode directly from the 3L mode. Being able to change from the 3L mode to the 2L mode without an intermediate state and back to the 3L mode from the 2L without an intermediate state may enable the control circuitry **76** to respond to flycap **80** voltage changes relatively quickly since delay associated with switching into the intermediate state is bypassed.
[0059] In a 2L mode, the buck converter **72** may be operated to change four switches at a time (e.g., two switches open and two switches close). The control circuitry **76** may operate the buck converter the control circuitry **76** is able to switch directly between the CD mode and the AB mode. The 2L mode switching may be operated like a larger compounded switch, relative to 3L mode switching operations. The control circuitry **76** may change operation of the buck converter **72** between these mode states without first entering into an intermediate switch state of AC mode or BD mode. This enables the control circuitry **76** to operate the buck converter **72** in the 2L mode directly from the 3L mode. While in the 2L mode, the control circuitry **76** may operate the buck converter **72** repeatedly between the CD mode and the AB mode. In the 2L mode, the charge stored by the flycap **80** may not be charged or discharged by the buck converter **72**. This may be caused by the flycap **80** being electrically isolated from the inductor current while the buck converter **72** is operated in either the CD mode and AB mode. Since the 2L mode involves operationally switching between the CD mode and the AB mode, the flycap **80** may be electrically isolated from the inductor current while the buck converter **72** is in either the CD mode or the AB mode.
[0060] In any of these modes, one switch may open at an at least partially overlapping time during to another switch closing to implement the mode change. Non-overlapping switching times may be used in some cases.
[0061] Referring now to FIGS. **9**A-**9**D in parallel with FIG. **8**, while the control circuitry **76** operates the buck converter **72** in the 2L mode to switch between the CD mode and the AB mode, the flycap **80** is isolated from the inductor **82**. The control circuitry **76** may operate the buck converter **72** into the 2L mode when the control circuitry **76** determines that the flycap **80** is to have its stored charge regulated to change the voltage across the flycap **80**. The control circuitry **76** may operate the buck converter **72** to be in a same output mode with a same switching frequency, as seen by the load **84**, without going to idle due to the additional 2L mode states and due to the ability to transition from the 2L mode states to the 3L mode states directly (bypassing the intermediate state) once the flycap **80** returns to desired voltage (e.g., returns to regulation).
[0062] To elaborate, the control circuitry **76** may receive, via a sensor **90**, sensed data **92** that indicates a charge at a time of sensing of the flycap **80**. The sensor **90** may be any suitable sensing circuitry, such as a voltage sensing circuit coupled in parallel with the flycap **80** to acquire a signal

indicative of the voltage across contacts of the flycap **80**. The sensed data **92** may indicate the voltage across the flycap **80** at the time of sensing.

[0063] The control circuitry **76** may compare the sensed data **92** to an indication of a target voltage value (e.g., a voltage set point). The control circuitry **76** may determine that the sensed data **92** crosses a threshold value. By making this determination, the control circuitry **76** may detect when the voltage output from the buck converter **72** is out of regulation independent of the direction of the inductor current (e.g., without determining the direction of the inductor current). The control circuitry **76** may respond by operating the buck converter **72** from the 3L mode into the 2L mode.

[0064] The 2L mode may isolate the flycap **80** from the inductor current while still enabling the flycap **80** to provide over voltage protection. Referring briefly to FIG. **8**, the control circuitry **76** may adjust the flycap **80** voltage, via the auxiliary circuitry **74**, without affecting the inductor current supplied to the load **84**. As shown in FIG. **8**, the control circuitry **76** may generate one or more control signals **88** (control signal **88**A, control signal **88**B, control signal **88**C) to operate switches **102** (switch **102**A, switch **102**B, switch **102**C) of the auxiliary circuitry **74**. The auxiliary circuitry **74** may include resistors **94** (resistor **94**A, resistor **94**B, resistor **94**C). The switches **102**A and **102**C, when enabled by the control circuitry **76** via the control signals **88**A and **88**C, may cause the auxiliary circuitry **74** to charge the flycap **80**. When the switches **102**A and **102**C are closed and the switch **102**B is open, the voltage supply (V.sub.IN) may electrically couple to the flycap **80** to cause a charging current to transmit through the flycap **80**. The switch **102**B, when enabled by the control circuitry **76** via the control signal **88**B, may cause the auxiliary circuitry **74** to discharge the flycap **80**. When the switch **102**B is closed and the switches **102**A and **102**C are open, the flycap **80** may discharge based on the resistor **94**B without being coupled to the voltage supply (V.sub.IN). The auxiliary circuitry **74** may include other components than those depicted in FIG. **8**, for example capacitors, inductors, resistors, voltage sources, switches, or the like, may be included.

[0065] When the control circuitry **76** determines that the sensed data **92** indicates the flycap **80** voltage is within regulation (e.g., within threshold range of deviation from a target threshold voltage), the control circuitry **76** may change the operation of the buck converter to return to the 3L mode. Being able to change from the 3L mode to the 2L mode without an intermediate state and back to the 3L mode from the 2L without an intermediate state may enable the control circuitry **76** to respond to changes in the flycap **80** voltage relatively quickly since delay associated with switching into the intermediate state is bypassed.

[0066] It is noted that the resistors **94**, capacitor **96**, and/or capacitor **98** may represent one or more system **70** and/or load **84** impedances, such as transmission path impendences or other impedances associated with the system **70**. The capacitors **96** and **98** may respective have two terminals or plates that connect to respective nodes associated with the buck converter **72**. Capacitor **96** may store a charge based on the input voltage (V.sub.IN) to the buck converter **72** and ground voltage (V.sub.SS). Capacitor **98** may store a charge based on the output voltage (V.sub.OUT) from the buck converter **72** and ground voltage (V.sub.SS).

[0067] As an example of these regulation operations, FIG. **10** is a flowchart of a method **110** performed by the control circuitry **76** to operate the buck converter **72** in the continuous conduction operation that permits zero-crossing of FIG. **7**. Any suitable device (e.g., a controller) that may control components of the electronic device **10**, such as the processor core complex **18**, may perform the method **110**. In some embodiments, the method **110** may be implemented by executing instructions stored in a tangible, non-transitory, computer-readable medium, such as the memory **20** or storage device **22**, using the processor core complex **18** and/or a processor of the control circuitry **76**. For example, the method **110** may be performed at least in part by one or more software components, such as an operating system of the electronic device **10**, one or more software applications of the electronic device **10**, and the like. While the method **110** is described using steps in a specific sequence, it should be understood that the present disclosure contemplates that the described steps may be performed in different sequences than the sequence illustrated, and certain described steps may be skipped or not performed altogether.

[0068] At block **112**, the control circuitry **76** may receive an indication of a target voltage of the flycap **80** (e.g., voltage set point) and a target voltage range (e.g., voltage operating range). The target voltage range may indicate a target range of voltages that the flycap **80** is to be operated within while operating the buck converter **72**. The indications of voltages may correspond to a current operational mode that the electronic device **10** is to be operated within, such as an always-on display mode, a powered off mode, a normal mode, or the like.

[0069] At blocks **114-118**, the control circuitry **76** may control operation of the buck converter **72** based on the indication of the flycap **80** voltage and the indication of the target voltage range. The control circuitry **76** may generate one or more control signals **86**, **88** to operate the buck converter **72** to discharge and charge the flycap **80** voltage as long as the voltage is within the target voltage range. These control operations may involve the control circuitry **76**, at block **114**, generating one or more control signals to operate the buck converter **72** to generate pulse frequency modulation (PFM) outputs. The control circuitry **76** may generate one or more control signals to start operation of the buck converter **72**, transitioning it out of an idle mode that had stopped output. At block **116**, the control circuitry **76** may determine to operate the buck converter **72** in a three-level (3L) continuous conduction (CC) pulse width modulation (PWM) mode. This determination may be based on the control circuitry **76** receiving an indication of the flycap **80** voltage that would correspond to the buck converter **72** generating an inductor current with a zero-crossing. At block **118**, the control circuitry **76** may generate one or more control signals to operate the buck converter **72** in the 3L PWM mode. These control signals may correspond to control signals **86**, which correspond to operating the buck converter **72** in one of the AB mode, BC mode, AC mode, or BD mode of FIGS. **9**A-D. The control circuitry **76** may continue to generate the various control signals **86** to operate the buck converter **72** between the various 3L modes. Some or all operations of blocks **114-118** may correspond to controlling, via control circuitry **76**, a multi-level buck converter to supply an output voltage to a load **84**, where the multi-level buck converter comprises a capacitor. Indeed, supplying the output voltage to the load **84** may involve being in the PFM mode and the PWM mode.

[0070] At block **120**, the control circuitry **76** may acquire, via the sensor **90**, first sensed data (e.g., the sensed data **92** at a first time) indicative of a voltage across the flycap **80** of the buck converter **72**. At some point during operation, the control circuitry **76** may confirm whether the flycap **80** voltage is within regulation according to the indications received at block **112**. The control circuitry **76** may confirm the regulation of the flycap **80** voltage at a sensing interval (e.g., once every minute, once every sensing interval, once every ten seconds). The sensing interval may be stored in memory and read by the control circuitry **76**. The control circuitry **76** may change the sensing interval in response to determining that the sensed flycap **80** voltage is a threshold from crossing the target voltage range (e.g., being out of range, 1%, 0.05%, 5% or any suitable threshold from being out of the target voltage range, 1V from crossing the target voltage range or any suitable voltage threshold).

[0071] At block **122**, the control circuitry **76** may determine that the sensed flycap **80** voltage is outside of the target voltage range based on comparing the first sensed data (e.g., the sensed data **92** at a first time) to the target voltage range and/or the indication of the target voltage. The control circuitry **76** may compare the first sensed data to the indication of the flycap **80** voltage. If the first sensed data is not equal to the flycap **80** voltage, the control circuitry **76** may compare the first sensed data to the target voltage range and determine whether the first sensed data is outside the target voltage range. The control circuitry **76** may do so based on the comparing (e.g., in response to the first sensed data being greater than the flycap **80** voltage) an upper limit of the target voltage range to the first sensed data and determining whether the first sensed data exceeds the upper limit and/or based on comparing (e.g., in response to the first sensed data being less than the flycap **80** voltage) a lower limit of the target voltage range to the first sensed data and determining whether the first sensed data is less than the lower limit. Basing the comparison of the first sensed data to the target voltage range on whether the first sensed data is less than or greater than the flycap **80** voltage may save one or more clock cycles of computation (e.g., be faster) based on eliminating one or more of the determination operations relative to checking both upper and lower limits each time.

[0072] In response to determining that the first sensed data is outside the target range of flycap **80** voltages, at block **124**, the control circuitry **76** may generate one or more control signals to operate the buck converter **72** in a two-level (2L) CC PWM mode corresponding to the AB mode and the CD mode of FIGS. **9**A and **9**C. While the buck converter **72** is in the 2L mode, the control circuitry **76** may continue to generate the control signals **86** to main the buck converter **72** in the 2L mode. The operations of block **124** may correspond to determining, via the control circuitry **76**, that a voltage of the capacitor (e.g., flycap **80**) crosses a threshold voltage and isolating, via the control circuitry **76**, the capacitor (e.g., flycap **80**) from the load **84** based on the voltage of the capacitor (e.g., flycap **80**) crossing the threshold voltage. By operating the buck converter **72** in the 2L mode, the flycap **80** may not have the inductor current transmitted through it. This may enable the control circuitry **76** to regulate, via the auxiliary circuitry **74**, the flycap **80** voltage without affecting operation of the load **84**.

[0073] Furthermore, while the buck converter **72** is in the 2L mode, at block **126**, the control circuitry **76** may generate one or more control signals **88** to charge or discharge the flycap **80** based on determining that the voltage is outside of the target voltage range. The control circuitry **76** may determine one or more adjustments to apply to the flycap **80** voltage to bring it within regulation (e.g., target voltage setpoint and target voltage range received at block **112**). The adjustment may involve operating one or more switches of the auxiliary circuitry **74** to discharge or charge the flycap **80** based on a difference between the voltage setpoint and the flycap **80** voltage. The control circuitry **76** may determine an amount by which to discharge the flycap **80** or an amount by which to charge the flycap **80**. The control circuitry **76** may adjust the flycap **80** voltage after the flycap **80** voltage is outside the target voltage range received at block **112**. In this way, the flycap **80** voltage may drift some and be stopped before drifting beyond the permissible range. Operations of block **126** may correspond to adjusting, via the control circuitry **76**, the voltage of the capacitor (e.g., flycap **80**) after the capacitor (e.g., flycap **80**) is electrically isolated from the load **84**.

[0074] After the control circuitry **76** operates the auxiliary circuitry **74** to charge or discharge the flycap **80**, at block **128**, the control circuitry **76** may acquire, via the sensor **90**, second sensed data (e.g., the sensed data **92** at a second time after the first time) indicative of a voltage across the flycap **80** of the buck converter **72**. At block **130**, the control circuitry **76** may determine that the sensed flycap **80** voltage is within the target voltage range based on comparing the second sensed data (e.g., the sensed data **92** at the second time) to the target voltage range and/or the target voltage. Operations of blocks **128** and **130** may correspond to determining, via the control circuitry **76**, that the voltage of the capacitor (e.g., flycap **80**) is within a target voltage range.

[0075] In response to the sensed flycap **80** voltage having returned to being in regulation, the control circuitry **76**, at block **132**, may generate control signals to operate the buck converter **72** to return to the 3L CC PWM mode. Operations of block **132** may correspond to controlling, via the control circuitry **76**, the buck converter **72** to electrically couple the capacitor (e.g., flycap **80**) to the load **84** based on the voltage of the capacitor (e.g., flycap **80**) being within the target voltage range.

[0076] Blocks **120-132** may correspond to incremental adjustments. In some cases, the control circuitry **76** implements the adjustment incrementally. Thus, the control circuitry **76** may determine one or more adjustments to apply to change the voltage to the target voltage over time (e.g., via multiple sensing and adjustment repeated operation).

[0077] The 3L CC PWM mode and the 2L CC PWM mode discussed with reference to FIG. **10** may be illustrated in FIG. **11**. FIG. **11** is a diagrammatic representation of a state diagram **150** of operations of the buck converter **72** when being operated in the continuous conduction operation that permits zero-crossing of FIG. **7**. The state diagram includes indications of operational states as state blocks **152-170**. States **172** correspond to idle states, where the inductor current may not be generated nor output from the buck converter **72**. States **174** correspond to 2L mode states, where the inductor current may be generated based on the control circuitry **76** operating the buck converter **72** to open and close pairs of switches **78** (e.g., paired switch **78**A and **78**B, paired switches **78**C and **78**D), as if a combination switch. States **176** correspond to 3L mode states, where the inductor current may be generated based on the control circuitry **76** operating the buck converter **72** into the different states **160-166** by opening and closing individual switches **78** over time as opposed to a combination switch.

[0078] The control circuitry **76** may operate the buck converter **72** in any of the states **172** or the state **152** corresponding to any pulse frequency modulation operation. Operations of block **114** may correspond to these operations.

[0079] From either of those states **152**, **154**, **156**, the control circuitry **76** may operate the buck converter **72** to a first AB mode (e.g., AB mode of FIG. **9**A) of state **158**. The state **158** enables subsequent transition directly to a respective of the states **174** (e.g., 2L mode) or the states **176** (e.g., 3L mode) without an additional intermediate state. From the state **158**, the control circuitry **76** may operate the buck converter **72** to the 3L mode states **176**. Operations of block **116-118** may correspond to these operations. To operate in the 3L mode states **176**, the control circuitry **76** may repeatedly generate various combinations of control signals **86** to operate the various switches **78** into the different 3L modes of FIGS. **9**A-**9**D. AB mode of FIG. **9**A corresponds to AB 3L mode of state **166**. AC mode of FIG. **9**B corresponds to AC 3L mode of state **164**. CD mode of FIG. **9**C corresponds to CD 3L mode of state **160**. BD mode of FIG. **9**D corresponds to BD 3L mode of state **162**. The state diagram **150** illustrates example transitions between the various 3L modes of states **176**. Operations of blocks **120** and **122** may occur in parallel with transitions between the various 3L modes of states **176**.

[0080] At some time, the control circuitry **76** may decide to operate the buck converter **72** in a respective 2L mode state of the states **174**. This may correspond to operations of block **122**. The operations of block **124** correspond to the control circuitry **76** generating one or more control signals **86** to operate the buck converter **72** from a respective 3L mode state of the states **176** into a respective 2L mode state of the states **174**. As indicated in the state diagram **150** and described above, no intermediate state may be used when transition from 3L mode to 2L mode. Indeed, the control circuitry **76** may directly transition the buck converter **72** to the 2L mode from the 3L mode (and later back again to the 3L mode or to one of the states **172**). While in the 2L mode, the control circuitry **76** may perform operations of block **126**, **128**, and **130**.

[0081] The control circuitry **76** may control the buck converter **72** from a respective 3L mode of the states **174** into a respective 3L mode of the states **176** (e.g., operations of block **132**). Indeed, the control circuitry **76** may directly transition the buck converter **72** to the 3L mode from the 2L mode. Operations of method **110** may be repeated via the control circuitry **76** to continue regulating power supplied via the buck converter **72** based on operating in and out of the 2L mode or 3L mode over time, as illustrated based on the state diagram **150**.

[0082] With the foregoing in mind, FIG. **12** is a plot **190** of a simulated voltage **192** of the flycap **80** over time (e.g., voltage waveform). The control circuitry **76** may control the buck converter **72** based on three regulation target voltage levels—a target voltage level **194**, an upper threshold level **196**, and a lower threshold level **200**. The setpoint voltage level corresponding to the flycap **80** may be represented on the plot **190** as target voltage level **194**. The voltage **192** waveform is depicted in FIG. **12** with regulating target-crossings. The buck converter **72** may be operated in the continuous conduction operation that permits zero-crossing of FIG. **7** (e.g., while operated in accordance with operations of method **110**) when the voltage **192** was simulated. As described herein, the control circuitry **76** may monitor the flycap **80** voltage and control the buck converter **72** in a 3L mode (e.g., between various states **176**) or a 2L mode (e.g., between states **174**) based on the monitored flycap **80** voltage.

[0083] The voltage **192** may correspond to the voltage across the flycap **80**. The voltage **192** may be regulated by the control circuitry **76** in accordance with the target flycap **80** voltage and target voltage range received at block **112** of method **110**. Between time=0 and time=t.sub.A, the voltage **192** averages to X, a positive non-zero voltage value equals the target voltage level **194** that may involve a zero-crossing (depending on the value of the target voltage level **194**). At time=t.sub.A the voltage **192** (e.g., average **198** of the waveform) beings to drift from the target voltage level **194**. The control circuitry **76** may continue to operate the buck converter **72** in the 3L mode (e.g., between respective states **176**) until the voltage **192** equals and/or crosses an upper threshold level **196**. The upper threshold level **196** may correspond to the target voltage range associated with block **112**.

[0084] At time=t.sub.B, the control circuitry **76** may operate the buck converter **72** in the 2L mode (e.g., between respective states **174**) to decouple the flycap **80** from the inductor **82** and enable regulation of the flycap **80** voltage to return within the target voltage range, as described above with operations of blocks **120-130**. Regulation of the flycap **80** voltage occurs while the buck converter **72** is in the 2L mode between time=t.sub.B and time=t.sub.D. Between time=t.sub.B and time=t.sub.D, corrections may be implemented to reduce an average of the voltage **192** over time.

[0085] At time=t.sub.C, the control circuitry **76** determines that the voltage **192** is within the target voltage range based on sensed data (e.g., operations of block **130**) and generates control signals to operate the buck converter **72** into the 3L mode (e.g., operations of block **132**).

[0086] Between time=t.sub.D and time=t.sub.E, the control circuitry **76** operates the buck converter **72** in the 3L mode and the average of the voltage **192** is within regulation and/or equals the target voltage level **194** from block **112**. The voltage **192** here corresponds to the positive non-zero voltage value that involves zero-crossings. At time=t.sub.E, the average **198** of the voltage **192** begins to drift negative. At time=t.sub.E, the control circuitry **76** determines that the average of the voltage **192** crosses a lower threshold level **200**. The 2L mode is once again used to isolate the flycap **80** from the load **84** and the control circuitry **76** is able to adjust the flycap **80** voltage within regulation without affecting operations of the load **84** and/or introducing additional switching harmonics since the power delivered to the load **84** may be undistributed by changing between the 2L and 3L modes.

[0087] The control circuitry **76** may control one or more buck converters **72**. Thus, operations of FIG. **10** may be performed in parallel at different times for different buck converters **72** powering different loads **84**.

[0088] In some systems, the electronic device **10** may be operated in various operational modes, such as an always-on display mode, a power off mode, a reduced power mode, and a normal mode, among others. These different operational modes may consume different amounts of power, which may lead to the power converter circuits associated with the PMUs **28** changing in operation to supply power while in the various operational modes. Through the controlled operations of the power converters, circuits of the electronic device **10** may receive different amounts of power corresponding to the different operational modes. For example, the control circuitry **76** may control a buck converter **72** to change a power supplied via a power rail to an integrated circuit being operated into a different operational mode. In one example operational mode, the integrated circuit may be operated in a low power mode. Similar to a power off mode, the PMU **28** may stop supplying power to one or more portions of the electronic device **10** while operated in the low power mode. With this in mind, entering the low power mode may entail reducing power supplied to one or more power rails. To operate the buck converter **72** to supply a different amount of power, control circuitry **76** may control the buck converter in the continuous conduction operation using systems and methods described herein to generate a negative current or a positive current, even as the generated current is around 0 A.

[0089] In some cases, different sub-systems of the electronic device **10** may be operated into different operational modes at a same time. In this way, a display **12** may be operated in an always-on display mode that corresponds to the image processing circuitry being in a powered off mode or a reduced power mode. Any suitable number of operational modes that combine reduced power mode, normal power modes, power off modes, or the like may be used, including power modes that power to different supply levels. The processor core complex **18** may transmit an indication of the operational mode to be implemented to the control circuitry **76**. In response, the control circuitry **76** may read indications of voltages (e.g., indication of the voltage of the flycap **80** and the target voltage range) from memory based on the indication of the operational mode, an identifier of the 3L buck converter, the load **84**, or the like. For example, a reduced power mode of a first sub-system may correspond to less power than a reduced power mode of a second sub-system and thus the control circuitry **76** may receive a different, lower indication of voltage of the flycap **80** when the load **84** is in the first sub-system relative to when the load **84** is instead in the second sub-system.

[0090] As noted above, around OA may refer to an output that involves a zero-crossing, an output that is suitably close to OA to be unreliable based on material properties, circuitry, and/or system design, or the like of that specific buck converter. These systems and methods may be used to generate the relatively small average inductor currents around 0 A that enable the low power mode described above. The average inductor current being around OA may correspond to an average inductor current of between 0 milliamps (mA) and 10 mA, 5 mA and 50 mA, 10 mA and 100 mA, 0.01 mA and 100 mA, 0 mA and 500 mA, or the like. Indeed, any suitable range with a zero-crossing in the inductor current waveform may be used.

[0091] Technical effects described herein include systems and methods that enable regulation of a three-level (3L) buck converter output around zero. Around zero may refer to an output that involves a zero-crossing, an output that is close to zero, or the like, where is close to zero means close enough to zero to be unreliable based on material properties, circuitry, and/or system design, or the like of that specific buck converter. A 3L buck converter operates based on a direction of a current generated between switches of the 3L buck converter. Current direction may become unpredictable or immeasurable around zero or when the waveform has a zero-crossing. For example, although an AC mode can be used to charge a flying capacitor (flycap) of the buck converter, when the inductor current generated is opposite in direction as to what control circuitry was expecting, the AC mode can discharge the flycap. Unexpected discharging or charging of the flycap may lead to power generated being out of regulation with target power to be supplied to a load. Described herein are control circuitry systems and methods that selectively switch the 3L buck converter between 2L modes and 3L modes to regulate the voltage output even if the inductor current is around zero (e.g., a relatively low average current target, includes a zero-crossing in its waveform, a threshold range from 0 A). Systems and methods described herein may compensate for flycap charge drift even with current direction detection being ambiguous when the output generated is around zero by using operating ranges to determine when to isolate the flycap from the load for charge regulation via an auxiliary circuit. By using these systems and methods herein, an output from buck converter may be regulated to a target output level (e.g., current, voltage, power) using continuous conduction operation that maintains a constant switching frequency without operating the output into tristate even if the output level is close to zero.

[0092] Furthermore, by using these systems and methods, a 3L buck converter may be used to replace a buck converter, such as in applications where the fixed frequency, low ripple on output, and controlled regulation when load is low are desired. Systems and methods described herein may be used to detect, as described, when the voltage of the flycap crosses a threshold. Thus, systems and methods may be used to control operation of a downstream circuit that operates based on the flycap voltage and/or the output from the 3L buck converter. The systems and methods of this disclosure may enable output overload and/or current limit detection corresponding to the

connected load. In the event that the current limit is detected, the described 3L buck converter may be responsively switched into an alternative state of the state diagram without an intermediate state. For example, the control circuitry may operate the 3L buck converter from the 3L mode to the 2L mode or to one of the idle states to not overload the connected load. Furthermore, the systems and methods of this disclosure may bootstrap voltages when crossing a threshold. For example, the switches of the 3L buck converter may use bootstrap control drivers. The 2L mode may be used to recover in less time from a bootstrap condition since in the 2L mode each of the four switches are turned on at some point during a clock period. In contrast, the 3L mode may leave some of the four switches off or unswitched over a clock period. Thus, the 2L mode may enable switch refreshing to occur in less than when in bootstrap condition relative using the 3L mode to switch refresh.
[0093] Examples described herein relate to PMUs and buck converters of the PMUs. It should be understood that buck converter systems and methods described herein may be applied to various circuitries within the electronic device.
[0094] The specific embodiments described above have been shown by way of example, and it should be understood that these embodiments may be susceptible to various modifications and alternative forms. It should be further understood that the claims are not intended to be limited to the particular forms disclosed, but rather to cover all modifications, equivalents, and alternatives falling within the spirit and scope of this disclosure.
[0095] Moreover, techniques presented and claimed herein are referenced and applied to material objects and concrete examples of a practical nature that demonstrably improve the present technical field and, as such, are not abstract, intangible or purely theoretical. Further, if any claims appended to the end of this specification contain one or more elements designated as “means for [perform]ing [a function] . . . ” or “step for [perform]ing [a function] . . . ”, it is intended that such elements are to be interpreted under 35 U.S.C. 112(f). However, for any claims containing elements designated in any other manner, it is intended that such elements are not to be interpreted under 35 U.S.C. 112(f).
[0096] It is well understood that the use of personally identifiable information should follow privacy policies and practices that are generally recognized as meeting or exceeding industry or governmental requirements for maintaining the privacy of users. In particular, personally identifiable information data should be managed and handled so as to minimize risks of unintentional or unauthorized access or use, and the nature of authorized use should be clearly indicated to users.

Claims

1. A system, comprising: a buck converter configured to power a load, wherein the buck converter comprises a capacitor; auxiliary circuitry coupled to the capacitor; and control circuitry configured to couple to the buck converter and the auxiliary circuitry, wherein the control circuitry is configured to: determine that a voltage of the capacitor crosses a threshold voltage; control the buck converter to isolate the capacitor from a current configured to be delivered to the load based on the voltage of the capacitor crossing the threshold voltage; and control the auxiliary circuitry to adjust the voltage of the capacitor based on the capacitor being isolated from the current.
2. The system of claim 1, wherein the control circuitry is configured to: determine that the voltage of the capacitor is within a target voltage range; and control the buck converter to electrically couple the capacitor to the current based on the voltage of the capacitor being within the target voltage range.
3. The system of claim 1, wherein the buck converter comprises a plurality of transistors comprising a first transistor, a second transistor, a third transistor, and a fourth transistor, wherein the first transistor and the second transistor are coupled to form a first node, wherein the second transistor and the third transistor are coupled to form a second node, wherein the third transistor

and the fourth transistor are coupled to form a third node.
4. The system of claim 3, wherein the control circuitry is configured to operate the buck converter into different modes based on respective transistor pairs of the plurality of transistors being turned on at a same time, wherein the different modes comprise an AB mode, a BD mode, a CD mode, and an AC mode, and wherein: the AB mode corresponds to the first transistor being on and the second transistor being on, the BD mode corresponds to the second transistor being on and the fourth transistor being on, the CD mode corresponds to the third transistor being on and the fourth transistor being on, and the AC mode corresponds to the first transistor being on and the third transistor being on.
5. The system of claim 4, wherein the control circuitry is configured to operate the buck converter into a two-level (2L) mode and a three-level (3L) mode, wherein the 2L mode corresponds to the control circuitry switching operation of the buck converter between the AB mode and the CD mode, and wherein the 3L mode corresponds to the control circuitry switching operation of the buck converter between the CD mode, the BD mode, the AC mode, and the AB mode.
6. The system of claim 5, wherein the control circuitry is configured to operate control the buck converter to isolate the capacitor from the current at least in part by operating the buck converter from the 3L mode to the 2L mode.
7. The system of claim 3, wherein the capacitor comprises a first terminal and a second terminal, wherein the first terminal is coupled to the first node, and wherein the second terminal is coupled to the third node.
8. The system of claim 7, wherein the voltage across the capacitor, when tracked over time, corresponds to a voltage waveform that crosses a target average voltage value.
9. The system of claim 1, wherein the current comprises a current waveform with a zero-crossing.
10. A non-transitory, tangible, computer-readable medium comprising instructions that, when executed by a processor, are configured to cause control circuitry to perform operations comprising: determining that a voltage of a capacitor crosses a threshold voltage, wherein a multi-level buck converter comprises a plurality of switches and the capacitor; isolating, via the plurality of switches, the capacitor from a current delivered to a load based on the voltage of the capacitor crossing the threshold voltage; adjusting the voltage of the capacitor after the capacitor is electrically isolated from the current; determining that the voltage of the capacitor is within a target voltage range associated with the threshold voltage; and coupling, via the plurality of switches, the capacitor to the load based on the voltage of the capacitor being within the target voltage range.
11. The non-transitory, tangible, computer-readable medium of claim 10, wherein adjusting the voltage of the capacitor after the capacitor is electrically isolated from the current comprises: determining an amount by which to discharge the capacitor; and performing multiple adjustment operations to discharge the voltage of the capacitor by the amount over time.
12. The non-transitory, tangible, computer-readable medium of claim 10, wherein isolating, via the control circuitry, the capacitor from the current comprises: controlling, via the control circuitry, a first pair of switches of the plurality of switches to turn on, wherein the first pair of switches is configured to couple to an input voltage, a first contact of the capacitor, an inductor; and controlling, via the control circuitry, a second pair of switches of the plurality of switches to turn off, wherein the second pair of switches is configured to couple to a ground voltage, a second contact of the capacitor, and the inductor.
13. The non-transitory, tangible, computer-readable medium method of claim 10, wherein isolating the capacitor from the current occurs at an at least partially overlapping time as controlling another multi-level buck converter to supply a different output voltage to another load.
14. The non-transitory, tangible, computer-readable medium of claim 10, wherein determining that the voltage of the capacitor crosses the threshold voltage comprises: determining to operate the multi-level buck converter in a first power mode based on determining to operate the load in the first power mode, wherein the multi-level buck converter is configured to be operated in a plurality

of power modes as a power mode of the load changes; and receiving the threshold voltage and the target voltage range based on the first power mode.

15. The non-transitory, tangible, computer-readable medium of claim 10, wherein the voltage of the capacitor comprises a voltage waveform that crosses a target average voltage value.

16. A non-transitory, tangible, computer-readable medium comprising instructions that, when executed by a processor, are configured to cause control circuitry to perform operations comprising: receiving an indication of a voltage set point and a voltage operating range corresponding to a power mode of a load, wherein a buck converter is configured to supply the load with power based on the voltage set point and a voltage of a flying capacitor; determining that the voltage of a capacitor is outside the voltage operating range; controlling the buck converter to isolate the capacitor from the load based on the voltage of the capacitor being outside the voltage operating range; and controlling auxiliary circuitry coupled to a plurality of nodes of the buck converter to adjust the voltage of the capacitor based on the capacitor being electrically isolated from the load.

17. The non-transitory, tangible, computer-readable medium of claim 16, wherein the operations comprise: determining that the voltage of the capacitor is within a target voltage range; and coupling the capacitor to the load based on the voltage of the capacitor being within the target voltage range.

18. The non-transitory, tangible, computer-readable medium of claim 16, wherein the operations comprise: receiving an additional indication of an additional voltage set point and an additional voltage operating range corresponding to an additional power mode of the load, wherein the load operated in the power mode is configured to use less power than in the additional power mode.

19. The non-transitory, tangible, computer-readable medium of claim 16, wherein the voltage of the capacitor corresponds to a voltage waveform that crosses a target average voltage value.

20. The non-transitory, tangible, computer-readable medium of claim 16, wherein controlling the buck converter to electrically isolate the capacitor from the load comprises operating the buck converter from a three-level mode to a two-level mode configured to isolate the capacitor through pairs of transistors switching.