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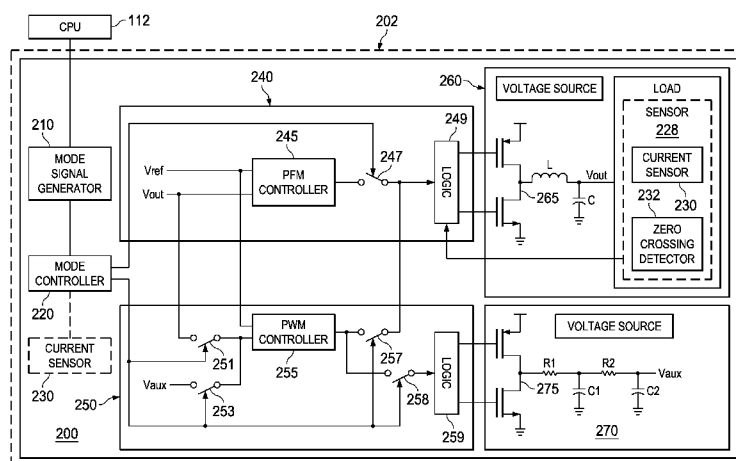
(54) **Title:** FAST MODE TRANSITIONS IN A POWER CONVERTER

FIG. 2

(57) **Abstract:** In described examples, a power conversion system includes a PFM controller (245), a PWM controller (255), and an auxiliary voltage output stage (270). The PFM controller (245) controls a power output stage (260) in a PFM mode in response to a power stage voltage output generated by the power output stage (260) during a first period of time in which the power output stage (260) is operating in the PFM mode. The PWM controller (255) controls the power output stage (260) in a PWM mode in response to a power stage voltage output generated by the power output stage (260) during a second period of time in which the power output stage (260) is operating in the PWM mode. The auxiliary voltage output stage (270) generates an auxiliary voltage during a third period of time, where the PWM controller (255) controls the auxiliary voltage output stage (270) using the auxiliary voltage during the third period of time.

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FAST MODE TRANSITIONS IN A POWER CONVERTER

BACKGROUND

[0001] Many communication systems, which often include wireless devices that both transmit and receive, operate in accordance with data transmission standards. Often, the data transmission standards specify relatively strict spectral mask requirements, which specify reduced amounts of noise, such as electromagnetic interference (EMI), during data transmission. The transmitter of such communication devices includes a power amplifier (PA) that is operable to transmit data in accordance with a data transmission standard. The PA typically receives power from a power converter, such as a DC-DC (direct current-to-direct current) converter. The power converter typically operates in a pulse-width modulation (PWM) mode during transmission to increase EMI compliance. The operating load on the power converter typically varies during operation of the communication device. For example, the operating load typically is relatively low while the system is in receive mode, during which time of operation the PA (and the power converter) is optionally turned off to conserve power. The power converter can be turned off, because it is normally inefficient to operate the power converter in a PWM mode during such times of low operating loads.

[0002] However, turning the power converter on again entails a relatively long wakeup time (e.g., on the order of hundreds of microseconds), during which the transmitter is not available for transmitting. The power converter can be switched to run in a relatively more efficient pulse-frequency modulation (PFM) mode during such low-load periods, but during the transition back to a PWM mode for a higher-load transmission period typically requires a settling time on the order of a few tens of microseconds. Such settling times exceed the settling requirements of some applications.

SUMMARY

[0003] The problems noted above can be solved in a fast mode-transitioning power converter. In described examples, the disclosed power converter includes a PFM controller, a PWM controller, and an auxiliary voltage output stage. The PFM controller controls a power output stage in a PFM mode in response to a power stage voltage output generated by the power output stage during a first

period of time, in which the power output stage is operating in the PFM mode. The PWM controller controls the power output stage in a PWM mode in response to a power stage voltage output generated by the power output stage during a second period of time, in which the power output stage is operating in the PWM mode. The auxiliary voltage output stage generates an auxiliary voltage during a third period of time, where the PWM controller controls the auxiliary voltage during the third period of time.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. 1 shows an illustrative electronic device in accordance with example embodiments.

[0005] FIG. 2 is a schematic diagram illustrating a fast mode-transitioning power converter in accordance with example embodiments.

[0006] FIG. 3 is a waveform diagram illustrating switching waveforms and output voltages of a fast mode-transitioning power converter in accordance with example embodiments.

[0007] FIG. 4 is a waveform simulation illustrating switching waveforms, output voltages, and currents of a fast mode-transitioning power converter in accordance with example embodiments.

[0008] FIG. 5 is a flow diagram of the operation of a fast mode-transitioning power converter in accordance with example embodiments.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0009] The terms "coupled to" or "couples with" are intended to describe either an indirect or direct electrical connection. Thus, if a first device couples to a second device, that connection can be made through a direct electrical connection, or through an indirect electrical connection via other devices and connections.

[0010] FIG. 1 shows an illustrative computing device 100 in accordance with example embodiments. For example, the computing device 100 is, or is incorporated into, or is coupled (e.g. connected) to an electronic system 129, such as a computer, electronics control "box" or display, communications equipment (including transmitters or receivers), or any type of electronic system operable to process information. In various embodiments, the electronics system 129 is included in a telecommunications system (or a portion thereof, such as a transmitter-receiver or transceiver), and in more particular embodiments, a wireless and/or low-power transceiver.

[0011] In various embodiments, the computing device 100 includes a megacell or a system-on-chip (SoC), which includes control logic such as a CPU 112 (central processing unit), a storage 114 (e.g., random access memory (RAM)) and a power supply 110. For example, the CPU

112 can be a CISC-type (complex instruction set computer) CPU, RISC-type CPU (reduced instruction set computer), MCU-type (microcontroller unit), or a digital signal processor (DSP). The storage 114 (which can be memory such as on-processor cache, off-processor cache, RAM, flash memory, or disk storage) stores one or more software applications 130 (e.g., embedded applications) that, when executed by the CPU 112, perform any suitable function associated with the computing device 100.

[0012] The CPU 112 includes memory and logic that store information frequently accessed from the storage 114. The computing device 100 is often controlled by a user using a UI (user interface) 116, which provides output to and receives input from the user during the execution the software application 130. For example, the output is provided using the display 118, indicator lights, a speaker and/or vibrations. The input is received using audio and/or video inputs (such as using voice or image recognition), and electrical and/or mechanical devices such as keypads, switches, proximity detectors, gyros and accelerometers.

[0013] The CPU 112 and power supply 110 are coupled to I/O (input-output) port 128, which provides an interface that is configured to receive input from (and/or provide output to) networked devices 131. The CPU 112 and power supply 110 are also coupled to the power amplifier (PA) 125, which provides power to the electronic system 129. Although the PA 125 is illustrated as being included in the I/O port 128, in various embodiments the PA 125 is optionally physically separated from the I/O port 128. The networked devices 131 can include any device (including test equipment) capable of point-to-point and/or networked communications with the computing device 100. The computing device 100 is often coupled to peripherals and/or computing devices, including tangible, non-transitory media (such as flash memory) and/or cabled or wireless media. These and other input and output devices are selectively coupled to the computing device 100 by external devices using wireless or cabled connections. The storage 114 is accessible, such as by the networked devices 131. The CPU 112, storage 114, and power supply 110 are also optionally coupled to an external power supply (not shown), which is configured to receive power from a power source (such as a battery, solar cell, “live” power cord, inductive field, fuel cell or capacitor).

[0014] The power supply 110 includes power generating and control components for generating power to enable the computing device 100 to execute the software application 130. For example, the power supply 110 provides one or more power switches, each of which can be independently

controlled, which supply power at various voltages to various components of the computing device 100. The power supply 110 is optionally in the same physical assembly as computing device 100, or is coupled to computing device 100. The computing device 100 optionally operates in various power-saving modes, in which individual voltages are supplied (and/or turned off) in accordance with a selected power-saving mode and the various components arranged within a specific power domain.

[0015] In various embodiments, the power supply 110 is a switched-mode power supply (e.g., “converter”) that alternately stores and outputs energy. Such converters typically receive either a DC (direct current) or rectified AC (alternating current) voltage as an input voltage. Energy derived from the input voltage is temporarily stored in energy storage devices (such as an inductors and capacitors) during each switching cycle. A power switch in the converter is actuated (e.g., closed for a “turned on” state or opened for a “turned off” state) to control the amount of energy that is output. A filter is normally used to reduce ripple in the output DC voltage and current. Depending on the topology selected for the converter, the output DC voltage can be higher or lower than the input voltages. The output DC voltage can also be inverted with respect to the input voltage.

[0016] Switching converters typically operate in either a discontinuous mode or a continuous mode. In the discontinuous mode, converters completely de-energize the energy storage devices before the end of every switching cycle. Accordingly, no current flows in the energy storage devices at the start of every switching cycle in the discontinuous mode. In the continuous mode, converters normally do not completely de-energize the energy storage devices before the end of every switching cycle. Accordingly, the current in the energy storage devices operating in a continuous mode normally does not reach a point where current does not flow in the energy storage devices.

[0017] The discontinuous inductor current conduction mode (DCM) is a power mode that is used to improve light-load efficiency in switching power converters. Because many computing devices 100 typically operate in applications that present electrical loads that are in the light-to-medium load current range, the light-load efficiency of voltage regulators has a substantial impact of the power efficiency of a system.

[0018] The output of a converter is determined in part by the duty ratio. The duty ratio is the time period in which the switch is “on” divided by the time period of the switching cycle (e.g., in

accordance with the equation $D=T_{on}/T_p$). The switching cycle time period is typically equal to the time period in which the switch is “on,” plus the time period in which the switch is “off,” and plus any time period in which the switch is “idle” (where $T_p=T_{on}+T_{off}+T_{idle}$). The output voltage of the buck converter in CCM (continuous conduction mode) is theoretically equal to the input voltage multiplied by the duty ratio (e.g., in accordance with the equation: $V_{out}=V_{in}*D$). The ranges of values of T_{on} and T_{off} are typically selected during design time (e.g., to achieve an optimum efficiency from a given technology process node to meet mask specifications of wireless standards).

[0019] The disclosed power supply 110 includes a fast mode-transitioning power converter 138, which in turn includes an auxiliary voltage output stage. The fast mode-transitioning power converter is operable to provide a relatively low-power PWM mode of operation ("auxiliary PWM") for a PA power converter, having very low quiescent (no-load) currents, and which can be operated in parallel to the PFM mode. The auxiliary PWM mode can be introduced whenever the converter needs to provide a very low load current, and is operable to provide a rapid transition to the PWM mode of operation to meet application system demands. Accordingly, the fast mode-transitioning power converter provides a rapid settling time (e.g., which is often required by WLAN standards), while allowing the power converter to operate as much as possible in PFM mode (e.g., which helps minimize power consumption by the power converter).

[0020] In one example, the power supply 110 is a DC-DC converter operable to operate in a discontinuous conduction mode (DCM). As introduced above, the power supply 110 includes a fast mode-transitioning power converter 138. Although the fast mode-transitioning power converter 138 is illustrated as being included in the power supply 110 or as a single (e.g., logical) unit, various portions of the fast mode-transitioning power converter 138 are optionally included in the same module (e.g., as formed by a die as produced in semiconductor manufacturing) or in different modules.

[0021] The fast mode-transitioning power converter 138 is operable to provide a relatively low-power PWM mode of operation ("auxiliary PWM"). The auxiliary PWM mode is typically operated in parallel to (e.g., at the same time as operating in) operation of a PFM mode. The fast mode-transitioning power converter 138 is operable to provide rapid transitions between PFM and PWM modes. In various embodiments, the fast mode-transitioning power converter 138 is a buck converter or a buck-boost converter. In example embodiments, the fast mode-transitioning power

converter 138 includes an auxiliary voltage output stage (e.g., 270 of FIG. 2) that includes power switches (such as FET switches) and passive components selected in accordance with a target application.

[0022] FIG. 2 is a schematic diagram illustrating a fast mode-transitioning power converter 200 in accordance with example embodiments. The fast mode-transitioning power converter 200 includes a particular embodiment of the fast mode-transitioning power converter 138 of FIG. 1, and is optionally formed (e.g., in whole or in part) on a substrate 202. Generally described, the fast mode-transitioning power converter 200 includes a mode signal generator 210, a mode controller 220, a sensor 228, a PFM controller 240, a PWM controller 250, a power output stage 260 (e.g., operable to generate a voltage output V_{out}), and an auxiliary voltage output stage 270 (e.g., operable to generate an auxiliary output voltage V_{aux}).

[0023] The mode signal generator 210 generates signals that are operable to select operation in a PFM mode or in a PWM mode voltage output. The mode signal generator can be operated in response to signals from a processor, such as a CPU 112 (as illustrated in FIG. 1). In various embodiments, the processor sends signals to the mode signal generator 210 in response to communications network protocols, such as network interface protocols that determine whether the electronic system 129 is in a receiving mode or a transmitting mode. For example, the mode signal generator 210 selects operating modes of the fast mode-transitioning power converter 200 in response to a selected transmission/receive mode of a transceiver. Accordingly, the fast mode-transitioning power converter 200 is operable to supply operating power in accordance with standards associated with a particular operating mode.

[0024] The mode signal generator 210 is coupled to the mode controller 220. For example, the mode controller 220 is operable to control timing of transitions and to buffer control signals. The optional current sensor 230 is operable to measure an operating load current. The mode signal generator 210 is optionally responsive to the sensor 228 (e.g., operable to select an operating mode in response to an operating current load). The sensor 228 includes a current sensor 230 and a zero crossing detector 232, both of which provide control information to control switches of the power output stage 260.

[0025] More particularly, the PFM controller 240 includes a PFM controller 245, a switch 247 and a logic unit 249, which drives the power stage 260. In the PFM controller 240, the PFM controller 245 is coupled to a voltage reference V_{ref} and the voltage output V_{out} , and to the switch

247 that controls the connection of the PFM controller 245 to the logic unit 249 that drives the power stage 260. The PWM controller 255 is coupled to a voltage reference V_{ref} and to the switch 251, which controls the connection of the PWM controller 255 to the voltage output V_{out} . The mode controller 220 is coupled to the switch 247 of the PFM controller 240. For example, when the fast mode-transitioning power converter 200 is operating in a PFM mode, the switch 247 is operable to selectively couple the output of the PFM controller 245 to the input of the logic unit 249.

[0026] Similarly, the PWM controller 250 includes a switch 251, a switch 253, a PWM controller 255, a switch 257, a switch 258, and a logic unit 259 that drives the auxiliary power stage 270. The PWM controller 255 is also coupled to the switch 253, which controls the connection of the PWM controller 255 to the auxiliary output voltage V_{aux} . The PWM controller 255 is also coupled to the switch 257, which controls the connection of the PWM controller 255 to the logic unit 249 of the PFM controller 240. The PWM controller 255 is also coupled to the switch 258, which controls the connection of the PWM controller 255 to the logic unit 259. The mode controller 220 is coupled to the switches 251, 253, 257, and 258 of the PWM controller 250.

[0027] For example, the switch 251 is operable to selectively couple the voltage output V_{out} to an input of the PWM controller 255 when the fast mode-transitioning power converter 200 is operating in a PWM mode. The switch 257 is operable to selectively couple the output of the PWM controller 255 to the input of the logic unit 249 that drives the power stage 260. To increase the speed of transitioning to the PWM mode, the switch 258 is operable to selectively couple the output of the PWM controller 255 to the input of the logic unit 249 (which in turn activates the auxiliary voltage source 270) before entering the PWM mode. The switch 253 is closed (while the switch 251 is open), which couples the V_{aux} signal (generated by the auxiliary voltage generator 270) to the input of the PWM controller 255. Coupling the V_{aux} signal to the PWM controller before entering the PWM mode (e.g., while operating in a quiescent mode or a PFM mode) initiates stabilization of the PWM controller 250 control loop, without substantially interrupting the existing operating mode of the fast mode-transitioning power converter 250.

[0028] The power output stage 260 includes a power FET switch 265, which is operable to selectively couple a voltage source to a first terminal an energy storage element such as inductor L . A second terminal of the inductor L is coupled to the high side of capacitor C and to the output voltage node V_{out} . A load is optionally coupled to the node V_{out} and optionally includes the

current sensor 230. The power switch 265 is driven in response to outputs of the logic unit 249.

[0029] The auxiliary voltage output stage 270 includes a FET switch 275. The power FET switch 275 is operable to selectively couple a voltage source to an input terminal of a network that is operable to emulate the frequency response of passive components present in the output power stage 260. For example, the “LC” frequency response is emulated when controlling a buck converter. The passive network includes a first resistor R1 and a second resistor R2. A first capacitor C1 is coupled between a center node of the resistor network (e.g., between R1 and R2) and ground. A second capacitor C2 is coupled between an output terminal of the resistor network and ground. The output terminal of C2 provides the auxiliary voltage output Vaux. For example, the components R1, R2, C1 and C2 are formed on the same substrate as the PWM controller 250 (and the PFM controller 240) and are selected such that the loop of the PWM controller 250 that includes the feedback signal Vaux is stable. The power switch 275 is driven in response to outputs of the logic unit 259 of the PWM controller 250, such that the supply voltage is converted to Vaux. When not in use, the power switch 275 is optionally placed in an open state, such that the supply voltage is not coupled to the center node of the voltage divider and, accordingly, power consumption is reduced.

[0030] In operation, the mode signal generator 210 and the optional current sensor 230 provide input signals to the mode controller 220, which actuates (e.g., opens and closes) the switches of the PFM controller 240 and the PWM controller 250 in response to the input signals. To operate in a PFM mode (such as PFM-only mode), the mode controller 220 signals the switch 247 of the PFM controller 240 to close (e.g., while other switches of the PWM controller 250 remain open). Accordingly, the logic unit 249 of the PFM controller 240 is operable to control the output voltage Vout in response to PFM mode signals generated by the PFM controller 245.

[0031] In an auxiliary PWM mode, a PWM mode is operated in parallel with PFM mode, in order to facilitate a fast transition from operating in the PFM mode to the PWM mode. To enter the auxiliary PWM mode, the mode controller 220 signals the switches 253 and 258 of the PWM controller 250 to close. When the switches 253 and 258 are closed (and the switch 251 and 257 are open), the PWM controller 255 is arranged to compare the auxiliary voltage Vaux with (e.g., against) the voltage of Vref and, in response, generates control signals for regulating the auxiliary voltage Vaux (which is output by the auxiliary voltage output stage 270). Operating in the auxiliary PWM mode (in which the auxiliary voltage output stage 270 is operating) consumes

substantially less power than the power output stage 260 would otherwise consume when continuing to operate in the PWM mode of operation. For example, the reduction in power consumption results in increased operating times in restricted-power consumption applications (e.g., such as when operating from battery power).

[0032] To transition from operating in the PFM to operating in a (e.g., standard) PWM mode, the mode controller 220 signals the switches 251 and 257 of the PWM controller 250 to close (and switch 253 and 258 are opened). The voltage of V_{aux} is typically selected to be the same voltage as the nominal voltage of V_{out} such that the operating points of the PWM controller 250 settle to same values in both the cases: (a) when switches 253 and 258 are closed and switches 251 and 257 are open; and (b) when switches 253 and 258 are open and switches 251 and 257 are closed. The operating points in the just mentioned cases may differ slightly due to mismatch in the formation of on-chip components. For example, having similar operating points facilitates fast transitioning between operating modes. When the switches 251 and 257 are closed, the PWM controller 255 is arranged to compare the output voltage V_{out} against the voltage of V_{ref} and, in response, generates control signals for regulating the output voltage V_{out} .

[0033] When the mode controller 220 causes switches 251 and 257 of the PWM controller 250 to close (or, e.g., sometime shortly thereafter, the mode controller 220 opens the switch 247 of the PFM controller 240, which transfers the control of the power output stage 260 to PWM controller 250. After the PFM-to-PWM transition is complete, the auxiliary PWM mode is (e.g., optionally) disengaged by the mode controller 220 signaling the switches 253 and 258 to open (and the auxiliary voltage source 270 shut down). When the input to the mode controller 220 from the mode signal generator 210 indicates that the fast mode-transitioning power converter 200 is to transition from operating in a PWM mode back to operating in a PFM mode, the mode controller 220 signals the switch 247 to close, and (e.g., at approximately the same time) signals the switches 251 and 257 to open.

[0034] FIG. 3 is a waveform diagram illustrating switching waveforms and output voltages of a fast mode-transitioning power converter in accordance with example embodiments. Generally described, waveform diagram 300 illustrates changes in voltages and state over time of various signals of a fast mode-transitioning power converter. Waveform diagram 300 includes an enable PFM signal (EN_PFM) 310, an enable PWM signal (EN_PWM) 320, an enable auxiliary PWM signal (EN_AUXILIARY_PWM) 330, an output voltage (V_{out}) 340, and an auxiliary voltage

(Vaux) 350. The enable signals EN_PFM 310, EN_PWM 320, and EN_AUXILIARY_PWM 330 represent digital signals such as those generated by the mode signal generator 210 of the fast mode-transitioning power converter 200 illustrated in FIG. 2.

[0035] A low voltage for each of EN_PFM 310, EN_PWM 320, and EN_AUXILIARY_PWM 330 represents an "off" state, and a high voltage represents an "on" state. Vertical lines in the waveform diagram 300 demarcate particular periods of time, which occur during operation of the fast mode-transitioning power converter 138 and/or the fast mode-transitioning power converter 200.

[0036] The output voltage (Vout) 340 and the auxiliary voltage (Vaux) 350 represent the magnitude of these voltages over time as produced by the power output stage 260 and the auxiliary voltage output stage 270, respectively, illustrated in FIG. 2. The power output stage 260 is enabled by a positive transition of EN_PFM 310 such that the power output stage 260 begins to generate an output voltage (Vout). Vout 340 rises during an initial portion of the PFM mode 362 and fluctuates between a lower threshold voltage and a higher threshold voltage when regulation is achieved by the PFM controller 240 during a later portion of PFM mode 362.

[0037] In anticipation of entering a PWM mode (such as determined by a transceiver controller), the EN-AUXILIARY-PWM 330 is asserted and the auxiliary PWM mode (e.g., AUX-PWM period 372) is entered. When the EN-AUXILIARY-PWM 330 is asserted, Vaux 350 rises to a voltage that is approximately equal to the target voltage of Vout 340. Regulation is achieved by PWM controller 250 when Vaux 350 rises to the approximately equal target voltage.

[0038] After regulation is achieved by PWM controller 250 (or after a sufficient length of time, for example) during the auxiliary PWM mode, EN_PFM 310 is deasserted (e.g., negated) and EN_PWM 320 is asserted. At (e.g., around) this time, the PWM controller 250 (using Vaux 350 as a reference) is used to regulate the power output stage 260. Accordingly, the operation (e.g., achieving feedback stability) of the PWM controller 250 is bootstrapped, without being (e.g., yet) coupled to regulate the voltage Vout 340.

[0039] The PWM mode is entered (and the auxiliary PWM mode exited) around the time when the EN_AUXILIARY_PWM 330 is deasserted. When the EN_AUXILIARY_PWM 330 is deasserted, the PWM controller 250 regulates the power output stage 260 using the (e.g., selectively coupled) Vout 340 as a reference. In an embodiment, the signal Vaux 350 is decoupled from an input of the PWM controller 255 at this time such that the auxiliary voltage output stage

270 is no longer regulated, and accordingly Vaux 350 begins to droop.

[0040] In anticipation of exiting a PWM mode (such as determined by a transceiver controller), the EN_PWM 320 is deasserted and the PFM mode (e.g., PFM period 364) is entered. When the EN_PWM 320 is deasserted, EN_PFM 310 is asserted such that the PFM mode is entered as described above. Signal EN_AUXILIARY_PWM is optionally asserted at this time or asserted after time Tflex (time flex) 396 (e.g., to reduce power consumption over time Tflex 396). Regulation is achieved by PFM controller 240 when Vout 340 fluctuates between two threshold voltages.

[0041] In anticipation of entering the next PWM mode, an auxiliary PWM mode is used to bootstrap the PWM controller 259 as described above. Turning the PWM controller off when not (e.g., necessarily) needed (such as during a PFM mode) saves power, but requires additional time to bootstrap the PWM controller 250 when reactivating the PWM controller 250. Accordingly, using the auxiliary PWM mode to bootstrap the PWM controller 250 reduces the amount of time otherwise required to bootstrap the PWM controller 250 and reduces overall power consumption of the system by providing fast mode transitions.

[0042] Accordingly, PFM time periods 362, 364, and 366 are periods when the enable signal EN_PFM 310 is on such that the fast mode-transitioning power converter 138 is operating in a PFM mode. PWM time periods 372 and 374 are periods when the enable signal EN_PWM 320 is enabled and the fast mode-transitioning power converter 138 is operating in a PWM mode. AUX_PWM time periods 382, 384, and 386 are periods when the enable signal EN_AUXILIARY_PWM 330 is enabled and the fast mode-transitioning power converter 138 is operating in an auxiliary PWM mode, often at the same time that the fast mode-transitioning power converter 138 is operating in PFM mode.

[0043] Accordingly, the auxiliary voltage Vaux 350 provided by the auxiliary voltage output stage 270 (illustrated in FIG. 2) is operable to provide rapid power settling of Vout 340 during the transition from operation of the fast mode-transitioning power converter 138 in a PFM mode to operation in a PWM mode.

[0044] The Tflex (flexible time) time period 396 is a time period in which the enable signal EN_AUXILIARY_PWM 330 optionally remains off for a longer time (e.g., as shown by the portion 334 of EN_AUXILIARY_PWM 330) after the assertion on EN-PFM 310 in the first portion of PFM 364. The portion 354 of the auxiliary voltage (Vaux) waveform represents the

lower level of auxiliary voltage (Vaux) that is achieved by the auxiliary voltage output stage 270 (illustrated in FIG. 2) when the enable signal EN_AUXILIARY_PWM optionally remains off for the time period 396.

[0045] FIG. 4 is a waveform simulation illustrating switching waveforms, output voltages, and currents of a fast mode-transitioning power converter in accordance with example embodiments. Generally described, waveform diagram 400 illustrates waveforms of an enable PFM signal (EN_PFM) 410, an enable PWM signal (EN_PWM) 420, an enable auxiliary PWM signal (EN_AUXILIARY_PWM) 430, an output voltage (Vout) 440, an auxiliary voltage (Vaux) 450, a load current 460, an inductor current 470, and a supply current 480.

[0046] Waveform diagram 400 illustrates simulation results of the output voltages and measurements of the internal current of the fast mode-transitioning power converter 138 in response to a transition from operation in the PFM mode to the PWM mode. The (EN_AUXILIARY_PWM) 430 signal represents the operation the Vaux 450 regulation control signal during the auxiliary PWM mode. Initially, the enable PFM signal (EN_PFM) 410 is asserted at the start of the simulation. At a time corresponding to approximately 500.0 microseconds, the enable PWM signal (EN_PWM) 420 is asserted. At approximately 504.0 microseconds ("the PFM-to-PWM transition time point"), the enable PFM signal (EN_PFM) 410 is deasserted such that the fast mode-transitioning power converter transitions from PFM mode to PWM mode. At the PFM-to-PWM transition time point, a momentary lack of regulation (e.g., by using Vout, rather than Vaux, as the feedback signal) causes spikes in both the output voltage (Vout) 440 and the auxiliary voltage (Vaux) 450. The extent of the spikes reduces as the feedback loop stabilizes and the now-regulated voltages both settle into a consistent PWM mode pattern (e.g., in a relatively short period of time) at approximately 511.0 microseconds. The output voltage (Vout) 440 is regulated (e.g., by using Vout as the feedback signal) to maintain a voltage around 1.8 volts from approximately 511.0 microseconds onwards (over which time the auxiliary voltage Vaux 450 rises, such as due to lack of regulation while still being switched).

[0047] Similarly, the inductor current 470 (for example, in inductor L of the power output stage 260 illustrated in FIG. 2) starts flowing at the PFM-to-PWM transition time point and settles into a consistent PWM mode pattern by approximately 511.0 microseconds (e.g., even with the increase in the load current 460 that occurs at approximately 510.0 microseconds).

[0048] The supply current 480 is sourced by the inductor current 470. A small spike in the

supply current 480 occurs at the PFM-to-PWM transition time point and settles by approximately 511.0 microseconds. Accordingly, the presence of the auxiliary voltage (Vaux) 450, as produced by the auxiliary voltage output stage 270 for example, in response to the enable auxiliary PWM signal (EN_AUXILIARY_PWM) 430, allows the fast mode-transitioning power converter 138 to rapidly transition from PFM mode to PWM mode with power settling occurring within approximately 7 microseconds. Accordingly, the output voltage of the output voltage stage is regulated within a time that is less than around 8 microseconds after the start of the second period of time (e.g., wherein the output voltage is regulated at a variance that is around less than 1 percent in the power generated by the power output stage).

[0049] FIG. 5 is a flow diagram illustrating a method of operation of a power converter with an auxiliary voltage output stage in accordance with example embodiments. Program flow 500 begins in operation 510, in which the power converter with an auxiliary voltage output stage begins operating in a PFM mode. Program flow continues to operation 512.

[0050] In operation 512, the auxiliary voltage output stage of a power converter (optionally) begins operating in preparation for a potential transition to PWM mode. Such preparation includes applying power to unpowered portions of circuitry in the auxiliary voltage output stage. In various embodiments (e.g., such as in applications where the rate of power consumption is not currently a limiting factor), the auxiliary voltage output stage of a power converter remains powered up in a “warm” state. During the warm state, not all power is removed from the auxiliary voltage output stage (e.g., which reduces latency when switching between the PFM and the PWM modes. Program flow proceeds to operation 514.

[0051] In operation 514, the mode controller of the auxiliary voltage output stage receives signals from the mode signal generator. The signal mode generator generates signals for transitioning to the auxiliary PWM (AUX_PWM) mode. For example, the signals are generated in response to signals from a processor, which provide an indication of an operation mode (e.g., send or receive) of an electronic communications system. The signals from the processor optionally are generated in response to historical transmission patterns (send and receive modes over time represented in data stored in a database, for example) and/or generated in response to the expiration of predetermined timer values. Program flow continues to operation 516.

[0052] In operation 516, the mode controller of the power converter with an auxiliary voltage output stage determines whether a signal for continuing operation has been received. If so,

program flow continues to operation 520. If not, program flow terminates. Program flow is optionally reinitiated with commencement of program flow at operation 510.

[0053] In operation 520, the mode controller of the power converter with an auxiliary voltage output stage determines whether a signal for enabling operation in PWM mode has been received. If so, program flow continues to operation 522. If not, program flow waits (or e.g., restarts by proceeding to operation 510).

[0054] In operation 522, the mode controller of the power converter with an auxiliary voltage output stage determines whether the auxiliary PWM (AUX_PWM) mode is in operation. If so, program flow continues to operation 530. If not, program flow proceeds to operation 524.

[0055] In operation 524, the power converter with an auxiliary voltage output stage begins operating in auxiliary PWM (AUX_PWM) mode (which, for example, reduces latency of initializing the PWM controller by stabilizing the feedback loop of the PWM controller before the PWM mode is entered. Program flow continues to operation 530.

[0056] In operation 530, the power converter with an auxiliary voltage output stage begins operating in PWM mode, and at the same time or shortly thereafter, the power converter with an auxiliary voltage output stage ceases operating in PFM mode. Program flow continues to operation 532.

[0057] In operation 532, the power converter with an auxiliary voltage output stage optionally ceases operating in auxiliary PWM (AUX_PWM) mode in response to signals from a processor. For example, ceasing operation of the auxiliary PWM mode saves power otherwise used to power components used in the AUX_PWM mode. Program flow proceeds to operation 534.

[0058] In operation 534, the mode controller of the power converter with an auxiliary voltage output stage receives signals from the mode signal generator. Program flow continues to operation 536.

[0059] In operation 536, the mode controller of the power converter with an auxiliary voltage output stage determines whether a signal for continuing operation has been received. If so, program flow continues to operation 538. If not, program flow terminates. Program flow may optionally be reinitiated (e.g., restarted) with recommencement of program flow at operation 510.

[0060] In operation 538, the mode controller of the power converter with an auxiliary voltage output stage determines whether a signal enabling for operation in PFM mode has been received. If so, program flow continues to operation 540. If not, program flow proceeds to operation 534.

[0061] In operation 540, the power converter with an auxiliary voltage output stage begins operating in PFM mode, and at the same time or shortly thereafter, the power converter with an auxiliary voltage output stage ceases operating in PWM mode. Program flow continues to operation 512.

[0062] In various embodiments, the above-described components can be implemented in hardware or software, internally or externally, and share functionality with other modules and components as illustrated herein.

[0063] Modifications are possible in the described embodiments, and other embodiments are possible, within the scope of the claims.

CLAIMS

What is claimed is:

1. A converter, comprising:
 - a PFM (pulse frequency modulation) controller operable for controlling a power output stage in a PFM mode in response to a power stage voltage output generated by the power output stage during a first period of time in which the power output stage is operating in the PFM mode;
 - a PWM (pulse width modulation) controller operable for controlling the power output stage in a PWM mode in response to a power stage voltage output generated by the power output stage during a second period of time in which the power output stage is operating in the PWM mode; and
 - an auxiliary voltage output stage operable for generating an auxiliary voltage during a third period of time, wherein the PWM controller is operable for controlling the auxiliary power output stage in response to the auxiliary voltage during the third period of time.
2. The converter of claim 1, wherein the PWM controller is operable in response to a feedback signal.
3. The converter of claim 2, wherein the feedback signal is generated in response to the auxiliary voltage during the third period of time.
4. The converter of claim 3, wherein the feedback signal is generated in response to the power stage voltage output during the second period of time.
5. The converter of claim 1, comprising a mode controller that is operable to select an operating mode for the power output stage in response to an indication of a system state.
6. The converter of claim 5, wherein the operating mode of the power output state is one of the PWM mode and the PFM mode.
7. The converter of claim 5, wherein the indicated system state is one of a transmit state and a read state.
8. The converter of claim 1, wherein the auxiliary voltage output stage includes a voltage divider having a center node at which the auxiliary voltage is generated.
9. The converter of claim 8, wherein the center node is not coupled to a power source during the first period of time.
10. The converter of claim 1, wherein the feedback signal to the auxiliary voltage output stage is decoupled from the auxiliary voltage output stage during at least a portion of the first period of time.

11. The converter of claim 1, wherein the power stage voltage output generated by the power output stage while operating in the PFM mode includes more noise than the power stage voltage output generated by the power output stage while operating in the PWM mode.
12. A system, comprising:
an input-output port that is operable to send data in a transmit mode and to receive data in an input mode; and
a power converter that operable to supply power to the input-output port, wherein the power converter includes: a PFM (pulse frequency modulation) controller operable for controlling a power output stage in a PFM mode in response to a power stage voltage output generated by the power output stage during a first period of time in which the input-output port is operable to receive data in a receive mode; a PWM (pulse width modulation) controller operable for controlling the power output stage in a PWM mode in response to a power stage voltage output generated by the power output stage during a second period of time in which the input-output port is operable to receive data in an receive mode; and an auxiliary voltage output stage operable for generating an auxiliary voltage during a third period of time, wherein the PWM controller is operable for controlling the power output stage in response to the auxiliary voltage during the third period of time.
13. The system of claim 12, wherein the PWM controller is operable in response to a feedback signal, wherein the feedback signal is generated in response to the auxiliary voltage during the third period of time, and wherein the feedback signal is generated in response to the power stage voltage output during the second period of time.
14. The system of claim 12, wherein the auxiliary voltage output stage includes a voltage divider having a center node at which the auxiliary voltage is generated.
15. The system of claim 14, wherein the center node is not coupled to a power source during the first period of time.
16. The system of claim 12, wherein the output voltage of the output voltage stage is regulated within a time that is less than around 8 microseconds after the start of the second period of time.
17. A method, comprising:
controlling a power output stage in a PFM (pulse frequency modulation) mode in response to a power stage voltage output generated by a power output stage during a first period of time in which the power output stage is operating in the PFM mode;

controlling the power output stage in a PWM (pulse width modulation) mode in response to a power stage voltage output generated by the power output stage during a second period of time in which the power output stage is operating in the PWM mode; and

generating an auxiliary voltage during a third period of time , wherein the PWM controller is operable for controlling the power output stage in response to the auxiliary voltage during the third period of time.

18. The method of claim 17, wherein the output power stage is regulated in response to a feedback signal.

19. The method of claim 18, wherein the feedback signal is generated in response to the auxiliary voltage during the third period of time.

20. The method of claim 18, wherein the feedback signal is generated in response to the power stage voltage output during the second period of time.

21. The method of claim 17, comprising selecting an operating mode for the power output stage in response to an indication of a system state, wherein the operating mode of the power output state is one of the PWM mode and the PFM mode, and wherein the system state is one of a transmit mode and a receive mode.

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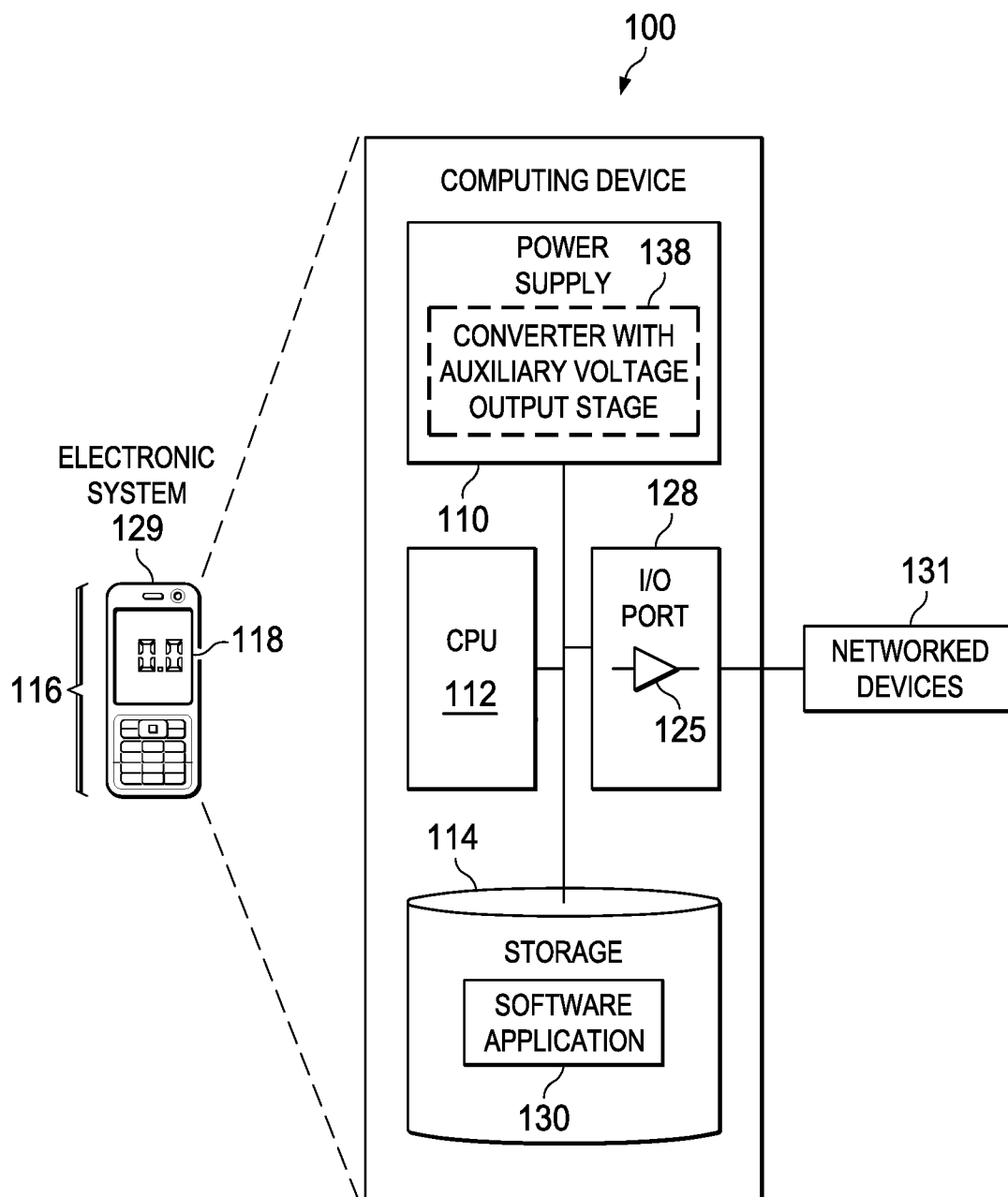


FIG. 1

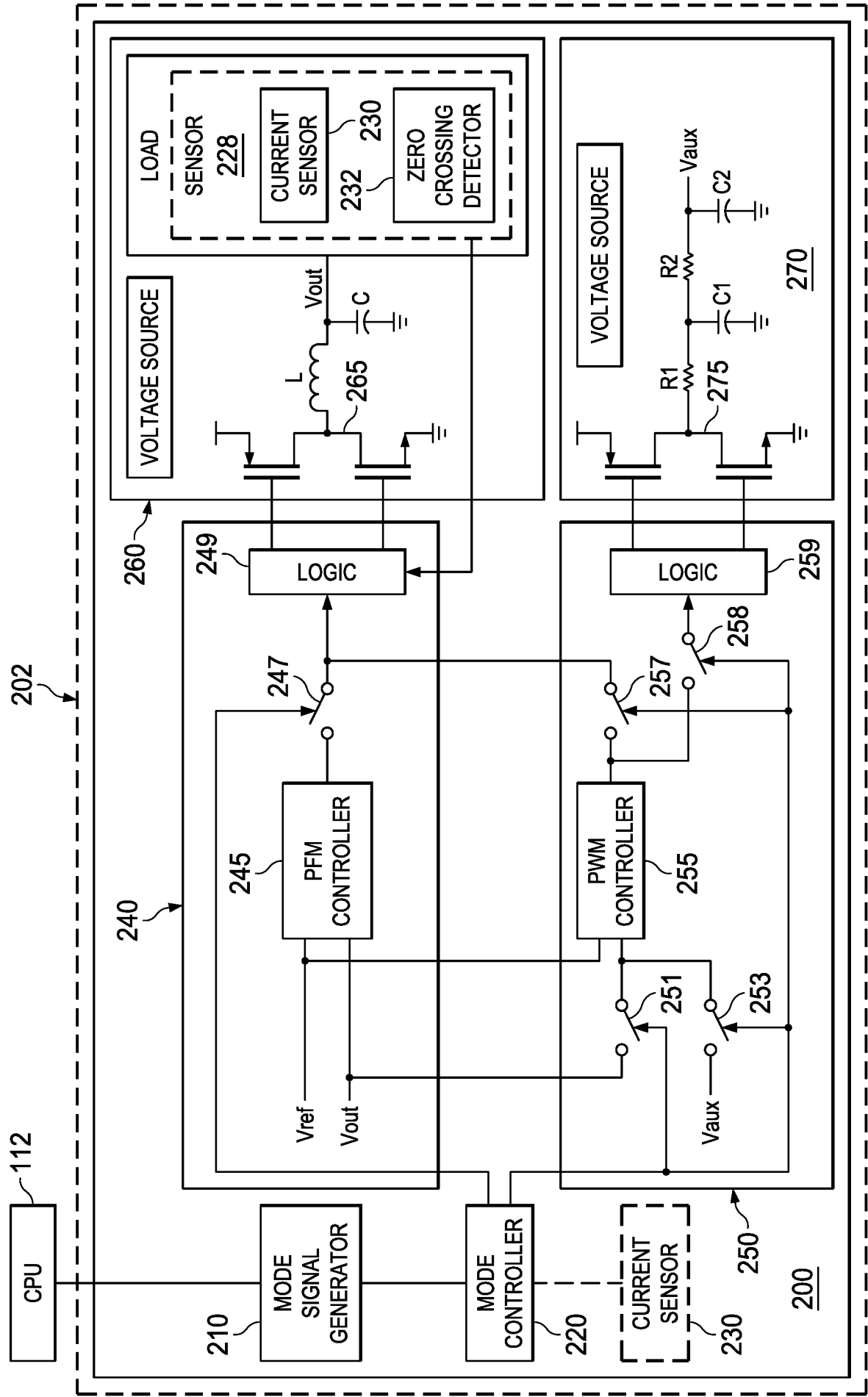


FIG. 2

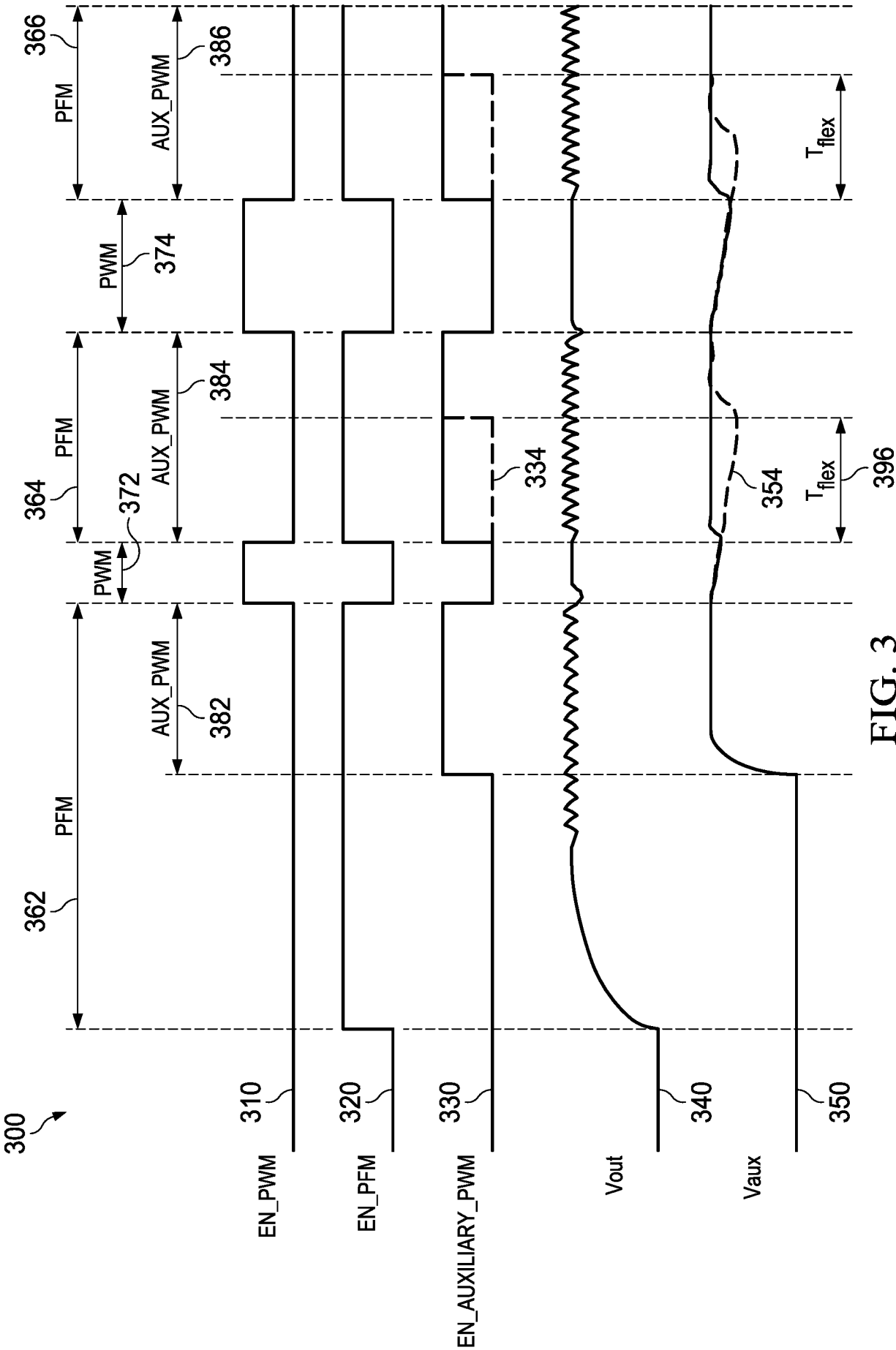


FIG. 3

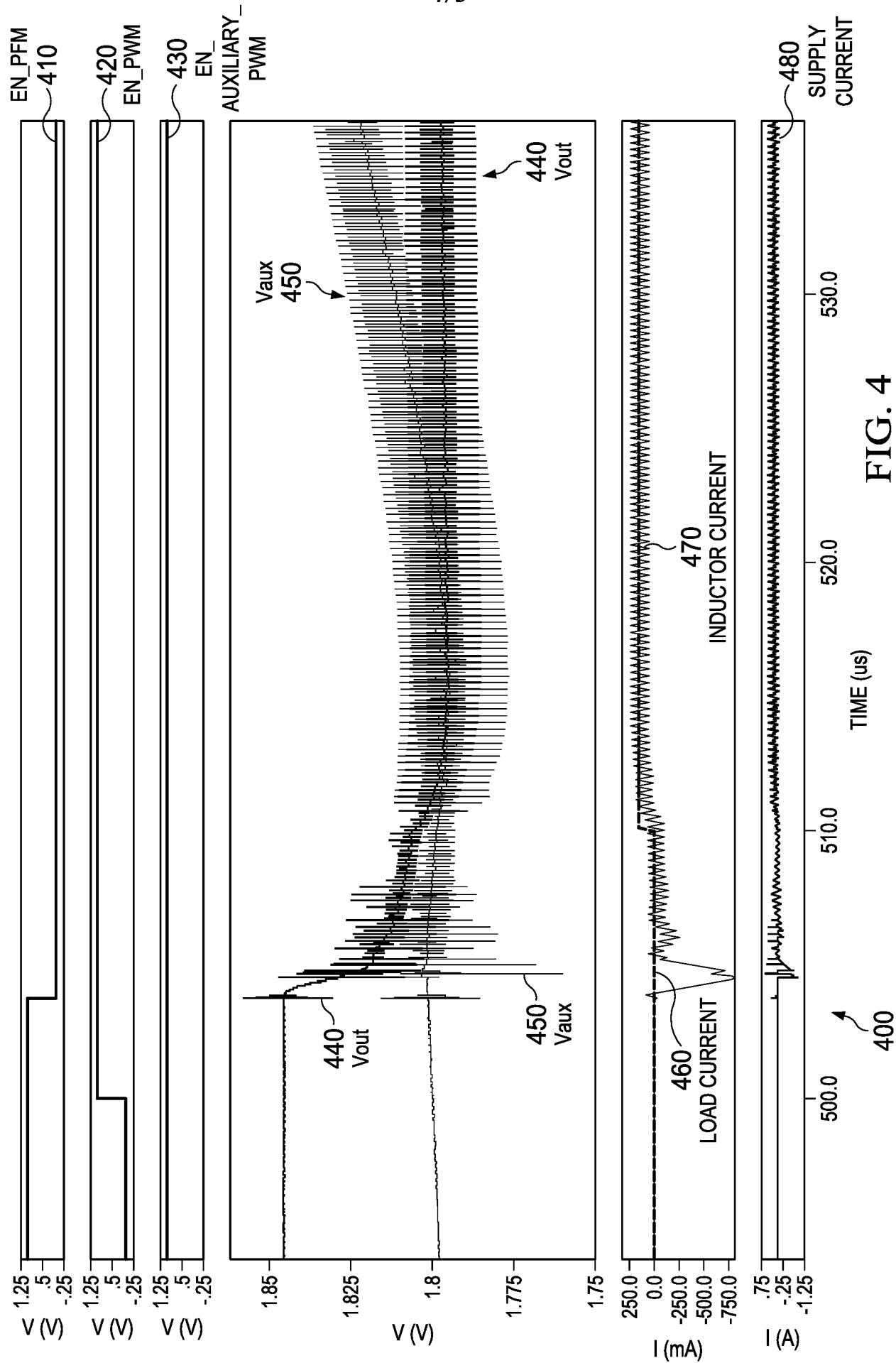


FIG. 4

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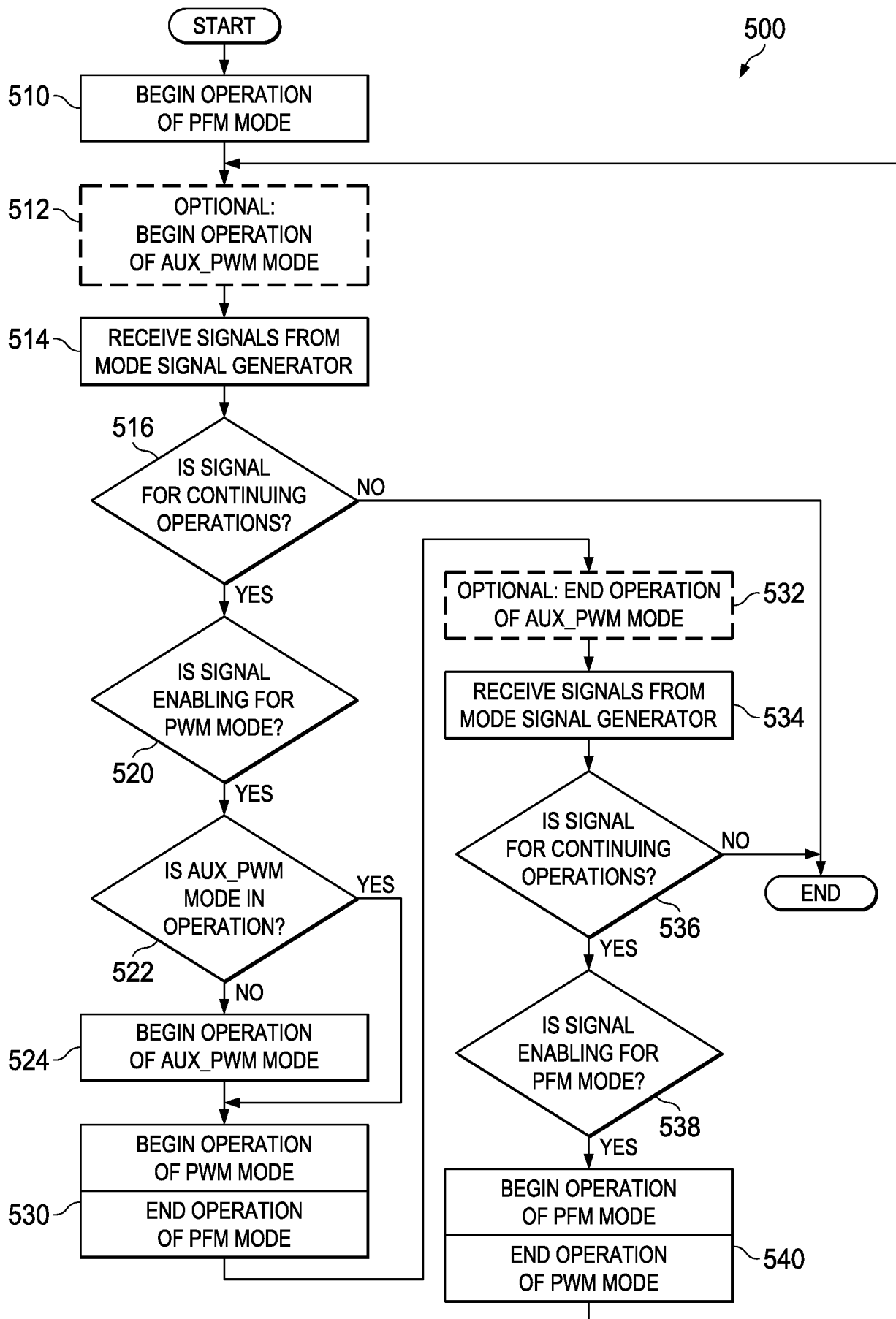


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2015/068313

A. CLASSIFICATION OF SUBJECT MATTER

H02M 3/158 (2006.01)**H02M 3/155 (2006.01)**

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 3/00-3/158, 7/00-7/155

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)

PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, DWPI, EAPATIS, PATENTSCOPE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013/0093407 A1 (HEO SEWAN et al.) 18.04.2013	1-21
A	US 2012/0200271 A1 (HENZLER STEPHAN et al.) 09.08.2012	1-21
A	JP 2003/0219637 A (TOHOKU PIONEER CORP) 31.07.2003	1-21
A	KR 20110035443 A (LG DISPLAY CO., LTD) 06.04.2011	1-21
A	WO 2007/076702 A1 (EMERSON NETWORK POWER ENERGY SYSTEMS AB et al.) 12.07.2007	1-21



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:	"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
"A" document defining the general state of the art which is not considered to be of particular relevance	"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
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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)	"&" document member of the same patent family
"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	

Date of the actual completion of the international search

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