



- (51) International Patent Classification:
G05F 1/56 (2006.01) *G05F 1/40* (2006.01)
- (21) International Application Number:
PCT/US2017/051670
- (22) International Filing Date:
14 September 2017 (14.09.2017)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
15/265,628 14 September 2016 (14.09.2016) US
- (63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 15/265,628 (CIP)
Filed on 14 September 2016 (14.09.2016)
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(54) Title: MULTIPHASE POWER CONTROLLER WITH DYNAMIC PHASE MANAGEMENT

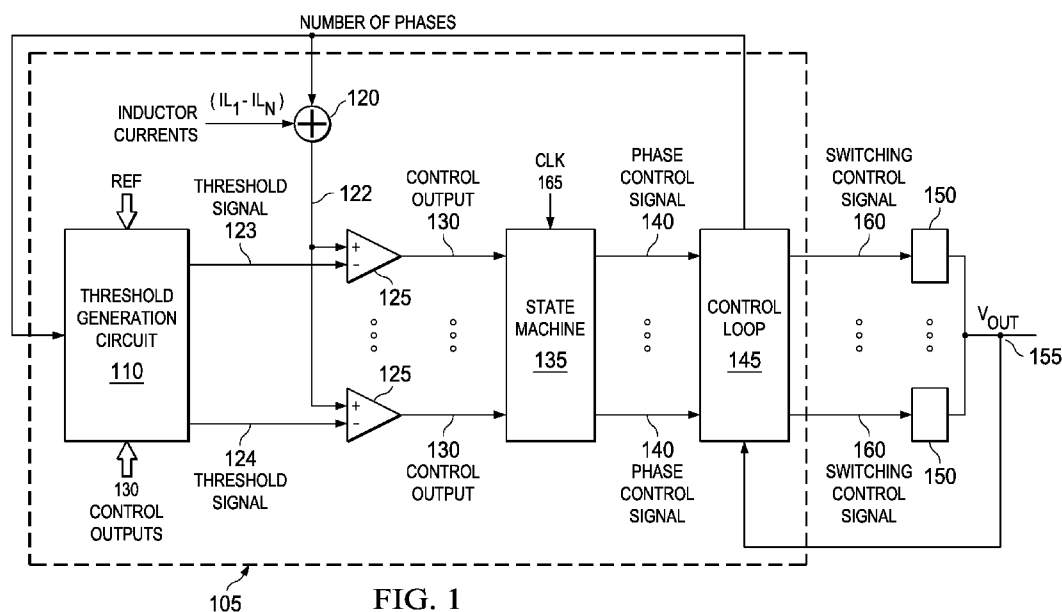


FIG. 1

(57) Abstract: In described examples, a multiphase power controller generates a set of switching control signals (160) to drive a set of power stages (150). The set of power stages (150) generates an output (V_{OUT}) that drives a load. The multiphase power controller includes a summer (120) to generate an equivalent voltage (122) representative of a sum of inductor currents from each of an inductor in the set of power stages (150). A threshold generation circuit (110) generates a set of threshold signals (123) in response to a set of control outputs (130) and a reference (REF). A set of comparators (125) generates the set of control outputs (130), in response to the equivalent voltage (122) and the set of threshold signals (123). A state machine (135) generates a set of phase control signals (140) in response to the set of control outputs (130). The set of control outputs (130) changes a number of the set of switching control signals (160).

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(81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

- *with international search report (Art. 21(3))*

MULTIPHASE POWER CONTROLLER WITH DYNAMIC PHASE MANAGEMENT

[0001] This relates to multiphase power controllers in integrated circuits.

BACKGROUND

[0002] In multiphase power supply systems, a load is divided into several regions. A multiphase power controller in such systems is divided into a number of phases that are assigned to a corresponding number of regions of the load. Normally, a one to one mapping exists between the number of phases and the regions of the load.

[0003] The multiphase power controller generates multiple PWM (pulse width modulation) outputs that drive multiple power stages. The multiphase power controller operates by sharing equal currents among all the phases. A power stage includes an inductor and a switching circuitry having a driver. Therefore, the current passing through the inductor in the power stages is shared equally, then added and delivered to the load. An “n” phase power controller provides “n” PWM outputs to “n” power stages. The PWM outputs are generated from the controller in response to the inductor currents and output voltage of the power stages in a closed loop.

[0004] In multiphase controllers, the load current is shared among the multiple phases even when the load current is low. Multiple power stages and other internal circuits continue to switch in such low load currents generating multiple PWM outputs. Accordingly, the PWM outputs are active for a 0 load current to a MAX load current. The PWM outputs being active at lower load conditions contributes to power consumption, conduction losses and switching losses affecting the efficiency of the multiphase power supply system.

SUMMARY

[0005] In described examples, a multiphase power system includes a multiphase power controller that generates a set of switching control signals to drive a set of power stages. The set of power stages generates an output that drives a load. The multiphase power controller includes a summer to generate an equivalent voltage representative of a sum of inductor currents from each of an inductor in the set of power stages. A threshold generation circuit generates a set of threshold signals in response to a set of control outputs and a reference. A set of comparators generates the set of control outputs, in response to the equivalent voltage and the set of threshold

signals. A state machine generates a set of phase control signals in response to the set of control outputs. The set of control outputs changes a number of the set of switching control signals.

[0006] In further described examples, a multiphase power controller includes a phase manage block that generates a set of phase control signals in response to an equivalent voltage and a threshold voltage. The multiphase power controller also includes a control loop that generates a set of switching control signals in response to the set of phase control signals. The set of switching control signals drive a set of power stages. The set of power stages generates an output that drives a load. The output is fed back to the control loop.

[0007] In described examples of an apparatus having a processor and a multiphase power controller coupled to the processor, the multiphase power controller generates a set of switching control signals that drive a set of power stages. The set of power stages generates an output that drives a load. The multiphase power controller includes a summer to generate an equivalent voltage representative of a sum of inductor currents from each of an inductor in the set of power stages. A threshold generation circuit generates a set of threshold signals in response to a set of control outputs and a reference. A set of comparators to generates the set of control outputs, in response to the equivalent voltage and the set of threshold signals. A state machine generates a set of phase control signals in response to the set of control outputs. The set of control outputs changes a number of the switching control signals.

[0008] In further described examples, a multiphase power system has a multiphase power controller having an inductor current input lead and a switching control output lead. The switching control output lead is coupled to a set of power stages. The multiphase power controller includes a summer having a first input coupled to the inductor current input lead and an output coupled to a first input of a set of comparators. A threshold generation circuit has an input and an output, the output connected to a second input of the set of comparators. A state machine has an input connected to outputs of the set of comparators. A control loop has a first input connected to a set of outputs of the state machine. The control loop has a set of first outputs connected to the switching control output lead. The control loop further has a second output coupled to a second input of the summer and the input of the threshold generation circuit. The set of power stages has an output coupled to a voltage output terminal. A second input of the control loop is coupled to the voltage output terminal. A load having an input is connected to the voltage output terminal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1 depicts a schematic of a multiphase power system according to an embodiment;

[0010] FIG. 2 depicts a threshold generation circuit according to an embodiment;

[0011] FIG. 3 depicts a power stage in the multiphase power system according to an embodiment;

[0012] FIG. 4 depicts a multiphase power controller with a load according to an embodiment; and

[0013] FIG. 5 depicts a summer in the multiphase power system.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0014] In various embodiments, a multiphase power controller monitors the phase currents in the system. The information about the phase currents is available in the multiphase power controller. Several embodiments introduce a technique that determines the phase currents of each inductor in power stages. Based on a threshold, which is predetermined, each phase is activated or inactivated per a load current requirement. Various embodiments calculate an optimum number of phases without sacrificing load and line regulation and yet maximize the efficiency for entire range of load currents.

[0015] FIG. 1 depicts a schematic of a multiphase power system according to an embodiment. The multiphase power system has a multiphase power controller 105 that generates a set of switching control signals 160. The switching control signals 160 drive the power stages 150, which regulates an output voltage (V_{out} , 155) and drives a load. A feedback from the output voltage (V_{out} , 155) to the control loop 145 keeps the output voltage regulated to a given voltage. The set of switching control signals 160 is configured to drive the load (such as a processor 405) connected to the output voltage (V_{out} , 155).

[0016] The multiphase power controller 105 has a threshold generation circuit 110 to generate a set of threshold signals 123, 124. The set of threshold signals 123 and 124 are generated in response to a set of control outputs and a reference as shown in FIG. 1. The set of control outputs are generated from a set of comparators 125. The set of threshold signals 123, 124 include an add signal and a drop signal. The threshold signals 123, 124 are generated using a set of summers (205, shown in FIG. 2 and later in this description). The threshold signals 123, 124 are fed to the set of comparators 125.

[0017] A summer 120 receives inductor currents (from the inductor 320 of each power stage 150) and converts the inductor currents to an equivalent voltage (V_{Isum}), on line 122. In various embodiments, the power stage also has a filter (such as an LC filter) having the inductor 320 and a capacitor 325 coupled to a node between the transistors 310.

[0018] The equivalent voltage V_{Isum} is fed to the set of comparators 125 along with the set of threshold signals 123 and 124. The equivalent voltage V_{Isum} is compared with two different threshold signals, the add signal (V_{th_add}) 123 and the drop signal (V_{th_drop}) 124. When the V_{Isum} is greater than V_{th_add}, the comparator output triggers and provides a pulse as a control output (130) to add a phase. When the V_{Isum} is lower than V_{th_drop}, the comparator output triggers and provides a pulse to a control output (130) to drop a phase. In one embodiment, the multiphase power controller 105 has only two comparators 125 irrespective of number of phases. In another embodiment, the thresholds for both the comparators 125 are independent. Therefore, the currents for adding a phase or dropping a phase are independently chosen.

[0019] The set of control outputs 130 includes a set of pulse width modulated (PWM) outputs. The control outputs 130 are connected to a state machine 135. The state machine 135 also receives a clock input 165. The clock input 165 is a system clock that synchronizes the operation of the multiphase power supply controller and several other circuits associated with the controller. The state machine 135 generates a set of phase control signals 140 in response to the control outputs 130. A control loop 145 receives the phase control signals. An output (switching control signal 160) of the control loop 145 is provided to the set of power stages 150.

[0020] The control loop 145 is shown as a block in FIGS. 1 and 2, and block has associated circuitry to enable the operation of the loop receiving inputs and generating corresponding outputs. Similarly, the state machine 135 is shown as a block and has associated circuitry to perform the functions of a state machine. In one embodiment, threshold generation circuit 110, comparators 125, state machine 135 together is referred to as a phase manage block. The phase manage block generates the phase control signals 140 that are provided to the control loop 145.

[0021] Each of the set of power stages 150 has a driver, a plurality of transistors, the inductor and a capacitor coupled to each other (as illustrated in FIG. 3). The set of phase control signals 140 include a phase add signal and a phase drop signal. The state machine 135 monitors the control outputs 130 and adds or drops the phase using phase control signals 140 (phase_add and phase_drop signals). Depending on phase_add and phase_drop signal status, the number of

phases is calculated in the state machine 135. The information about the number of phases is fed back to the summer 120 and the threshold generation circuit 110. The summer 120 decides on the number phase currents to be summed up. The state machine 135 has a counter that stores the active number of phases at a present state. For example, if the system is at n^{th} phase and a phase_add signal is received, the counter counts “ $n+1$ ”, and $n+1^{\text{th}}$ phase is activated.

[0022] Referring to FIG. 2, a threshold generation circuit 110 is illustrated according to an embodiment. The threshold signals (123, 124) are generated using summers 205. In the threshold generation circuit 110, the equivalent voltages (on lines 202 and 204) proportional to the inductor currents are generated by a long resistor ladder (not shown in the Figures). Top and bottom ends of resistor ladder are regulated by a precision voltage. The source and sink currents are connected to both regulated ends to minimize the impact of impedance of the resistor ladder.

[0023] In one embodiment, three programmable analog multiplexers dynamically select the thresholds for selecting a) common mode current b) phase add offset current and c) phase drop offset current. The currents are then converted to the equivalent voltage with fixed offset (V_{ref}). In one embodiment, current may also be controlled, in addition to or instead of the voltage, using techniques for current control instead of converting current to an equivalent voltage. The set of analog multiplexers (not shown in the Figures) in the system continuously sample the actual number of phases from the control loop 145. Based on the actual number of phases, the multiplexer output is selected for all the three analog multiplexers. The multiplexer outputs are fed to the summers 205. The summers 205 add the equivalent voltages (on lines 202 and 204), and generates the threshold signals based on the number of phases information from the control loop 145. Accordingly, the threshold generation circuit 110 is configured to change the threshold as per the number of phases.

[0024] The summer 120 is configured to add all inductor currents with offset (for phase_add and phase_drop signals). The summer uses total $(N+1)$ summing currents, where N is maximum number of phases. FIG. 5 depicts a summer 120. The summer 120 has 7 summing branches. Each summing portion has a switch 510 controlled by the output of the control loop 145 (number of phases). The maximum phases used is 6 in this example thereby needing are a total of 7 summing branches. The switch 510 is connected to a transistor 515. The transistor 515 is connected to a ground terminal through a resistor 520. The output voltage across resistor R2, 505 is the final summed output.

[0025] The current information is received at a gate of the transistor 515. Depending on the voltage, the current flows from resistor R2 505 to resistor R1 520. The current at the resistor R1 520 is directly proportional to the voltage at the gate of the transistor 515. Currents from each summer branch flows and adds to resistor R2 505. Output voltage V_{out} (of summer, 120) is proportional to (actual no. of phases)* $R2/R1$. Implementation of the summer 205 in FIG. 1 is similar to that of summer 120.

[0026] Referring again to FIG. 2, in one embodiment, the summers 120 and 205 are used to generate a final voltage for the threshold signals. This ensures that all the thresholds use the same network along with actual current so that any mismatches and PVT (process, voltage and temperature) variations are managed by optimizing devices and the circuit layout. In one embodiment, one summer (any of summer 120 or 205) is used three times instead of using two summers 205 and one summer 120. The current summers 120, 205 generate V_{Isum} and threshold signals (V_{th_add} and V_{th_drop} signals). V_{Isum} and threshold signals are fed to two comparators 125. The phase control signals 140 ($phase_add$ or $phase_drop$ signals) are generated based on the actual current, the add signal and the drop signal (threshold signals 123, 124). If V_{Isum} is less than the threshold voltage, the $phase_drop$ signal is generated and the number of phases is sequentially dropped by one phase. The phase control signals 140 indicate the optimum number of phases required for a particular load requirement. The phase drop operation may be defined as dropping (or removing) of a particular phase during DC operation. Phase drop in DC operation occurs when all the phase currents from the inductors are summed up and when V_{Isum} is less than the threshold voltage. A particular phase remains inactive until the state machine 135 generates the $phase_add$ signal based upon actual current. After an input is received from the state machine 135, that particular phase is added again. The state machine 135 operates continuously and adds or drops phases based on actual current and the output of the state machine 135 in a looped fashion.

[0027] During operation, the state machine 135 latches the control outputs 130 and generates phase control signals 140. The phase control signals 140 are provided to a control loop 145. The control loop 145 is configured to calculate and generate an updated number of phases. The updated number of phases is sent back to the threshold generation circuit 110 and summers 120 and 205 on line 210. A new set of threshold signals are generated thereafter and compared for meeting any criterion for adding or dropping the phases depending on the required efficiency of

the multiphase power system. The control loop 145 continues the operation till a last phase of the number of phases is reached in a changing load condition.

[0028] In one aspect, the number of phase change in multiphase power controller re-distributes the current in each inductor. The change in load current is sensed and compared with new thresholds. When the load current crosses add or drop threshold limits, the process repeats and the controller 105 is configured to decide whether to add or drop the phases. Monitoring of load or phase current is designed to operate continuously and the controller 105 adaptively decides the optimum number of phases. The multiphase power system has a fast transient response to adapt to change in load currents.

[0029] FIG. 3 depicts a power stage 150 in the multiphase power system. Each power stage 150 receives a switching control signal 305 input from the control loop 145. Generally, the number of power stages 150 is equal to the number of switching control signals 305. This example has “n” phase control signals and “n” power stages 150. Each power stage 150 has a plurality of transistors 310, a driver 315 connected to the gate of one transistor, a driver with an inverter 314 connected to the gate of the transistor 310, and a filter connected to the transistors. The filter has an inductor 320 and a capacitor 325. The inductor currents provided to the summer 120 are the currents flowing through the inductors 320 of each power stage 150. Each power stage 150 drives a load (such as load 405) connected to the output voltage Vout node 155. The output voltage Vout is fed back to the control loop 145 to dynamically change the set of control outputs as described hereinabove.

[0030] FIG. 4 depicts the multiphase power controller 105 with a load 405. The load 405, in one embodiment, is a processor configured to be driven by the power stages 150. The processor is a microprocessor in another embodiment. The output voltage 155 of the multiphase power controller 105 is connected to the processor 405. The load 405 draws current from the output voltage node (Vout, 155). The multiphase controller 150 of FIG. 4 is identical in connection and operation to the multiphase controller 105 of FIG. 1 and is not repeated here for the sake of simplicity.

[0031] Embodiments described herein can include any type of computerized device (e.g., a controller, microprocessor, digital signal processor) or other device configured with software and/or circuitry (e.g., a processor) to process any or all of the method operations described herein. Accordingly, embodiments herein can include a computerized device, such as a

computer or any type of processor that is programmed or configured to support operations such as those described herein.

[0032] In one embodiment, the multiphase power controller 105 is formed on a semiconductor die by conventional semiconductor manufacturing techniques. The semiconductor die also includes other circuits fabricated thereon.

[0033] 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 multiphase power system comprising:
a multiphase power controller that generates a set of switching control signals to drive a set of power stages, the set of power stages generating an output that drives a load, the multiphase power controller including: a summer to generate an equivalent voltage representative of a sum of inductor currents from each of an inductor in the set of power stages; a threshold generation circuit, coupled to the summer, to generate a set of threshold signals in response to a set of control outputs and a reference; a set of comparators to generate the set of control outputs, in response to the equivalent voltage and the set of threshold signals; and a state machine to generate a set of phase control signals in response to the set of control outputs, the set of control outputs changing a number of the set of switching control signals.
2. The multiphase power system of claim 1, wherein each of the set of power stages includes a driver, an inverter, a plurality of transistors, the inductor and a capacitor coupled to each other.
3. The multiphase power system of claim 1, wherein the set of control outputs includes a set of pulse width modulated (PWM) outputs.
4. The multiphase power system of claim 1, wherein:
the set of threshold signals include an add signal and a drop signal; and
the set of phase control signals include a phase add signal and a phase drop signal.
5. The multiphase power system of claim 1, wherein:
the threshold generation circuit generates the set of threshold signals from a resistor ladder; and
a top and a bottom end of the resistor ladder are regulated by a voltage.
6. A multiphase power controller comprising:
a phase manage block that generates a set of phase control signals in response to an equivalent voltage and a threshold voltage; and
a control loop that generates a set of switching control signals in response to the set of phase control signals, the set of switching control signals driving a set of power stages, the set of power stages generating an output that drives a load; wherein the output is fed back to the control loop.

7. The multiphase power system of claim 6, wherein the phase manage block includes:
 - a summer to generate an equivalent voltage representative of a sum of inductor currents from each of an inductor in the set of power stages;
 - a threshold generation circuit to generate a set of threshold signals in response to a set of control outputs and a reference;
 - a set of comparators to generate the set of control outputs, in response to the equivalent voltage and the set of threshold signals; and
 - a state machine to generate a set of phase control signals in response to the set of control outputs, the set of control outputs changing a number of the set of switching control signals.
8. The multiphase power system of claim 6, wherein each of the set of power stages comprises a driver, an inverter, a plurality of transistors, the inductor and a capacitor coupled to each other.
9. The multiphase power system of claim 6, wherein:
 - the set of threshold signals include an add signal and a drop signal; and
 - the set of phase control signals include a phase add signal and a phase drop signal.
10. The multiphase power system of claim 8, wherein each of the set of power stages comprises a driver, a plurality of transistors, the inductor and a capacitor coupled with each other.
11. The multiphase power system of claim 6, wherein the output is fed back to the control loop to dynamically change the number of the set of switching control signals.
12. An apparatus comprising:
 - a processor;
 - a multiphase power controller coupled to the processor, the multiphase power controller that generates a set of switching control signals to drive a set of power stages, the set of power stages generating an output that drives the processor, the multiphase power controller including:
 - a summer to generate an equivalent voltage representative of a sum of inductor currents from each of an inductor in the set of power stages;
 - a threshold generation circuit to generate a set of threshold signals in response to a set of control outputs and a reference;
 - a set of comparators to generate the set of control outputs, in response to the equivalent voltage and the set of threshold signals;
 - and a state machine to generate a set of phase control signals in response to the set of

control outputs, the set of control outputs changing a number of the set of switching control signals.

13. The apparatus of claim 12, wherein each of the set of power stages includes a driver, an inverter, a plurality of transistors, the inductor and a capacitor coupled to each other.

14. The apparatus of claim 12, wherein the set of control outputs includes a set of pulse width modulated (PWM) outputs.

15. The apparatus of claim 12, wherein:
the set of threshold signals include an add signal and a drop signal; and
the set of phase control signals include a phase add signal and a phase drop signal.

16. The apparatus of claim 12, wherein the multiphase power controller is formed on a semiconductor die.

17. A multiphase power system comprising:
a multiphase power controller having an inductor current input lead and a switching control output lead, the switching control output lead coupled to a set of power stages, the multiphase power controller including:

a summer having a first input coupled to the inductor current input lead and an output coupled to a first input of a set of comparators;

a threshold generation circuit having an input and an output, the output connected to a second input of the set of comparators;

a state machine having an input connected to outputs of the set of comparators;

a control loop having a first input connected to a set of outputs of the state machine; the control loop having a set of first outputs connected to the switching control output lead; the control loop having a second output coupled to a second input of the summer and the input of the threshold generation circuit; the set of power stages having an output coupled to a voltage output terminal; a second input of the control loop coupled to the voltage output terminal; and

a load having an input connected to the voltage output terminal.

18. The multiphase power system of claim 17, wherein the load is a microprocessor.

19. The multiphase power system of claim 17, wherein the outputs of the set of comparators generate the set of control outputs, and wherein the set of control outputs change a number of the set of switching control signals active at a given time.

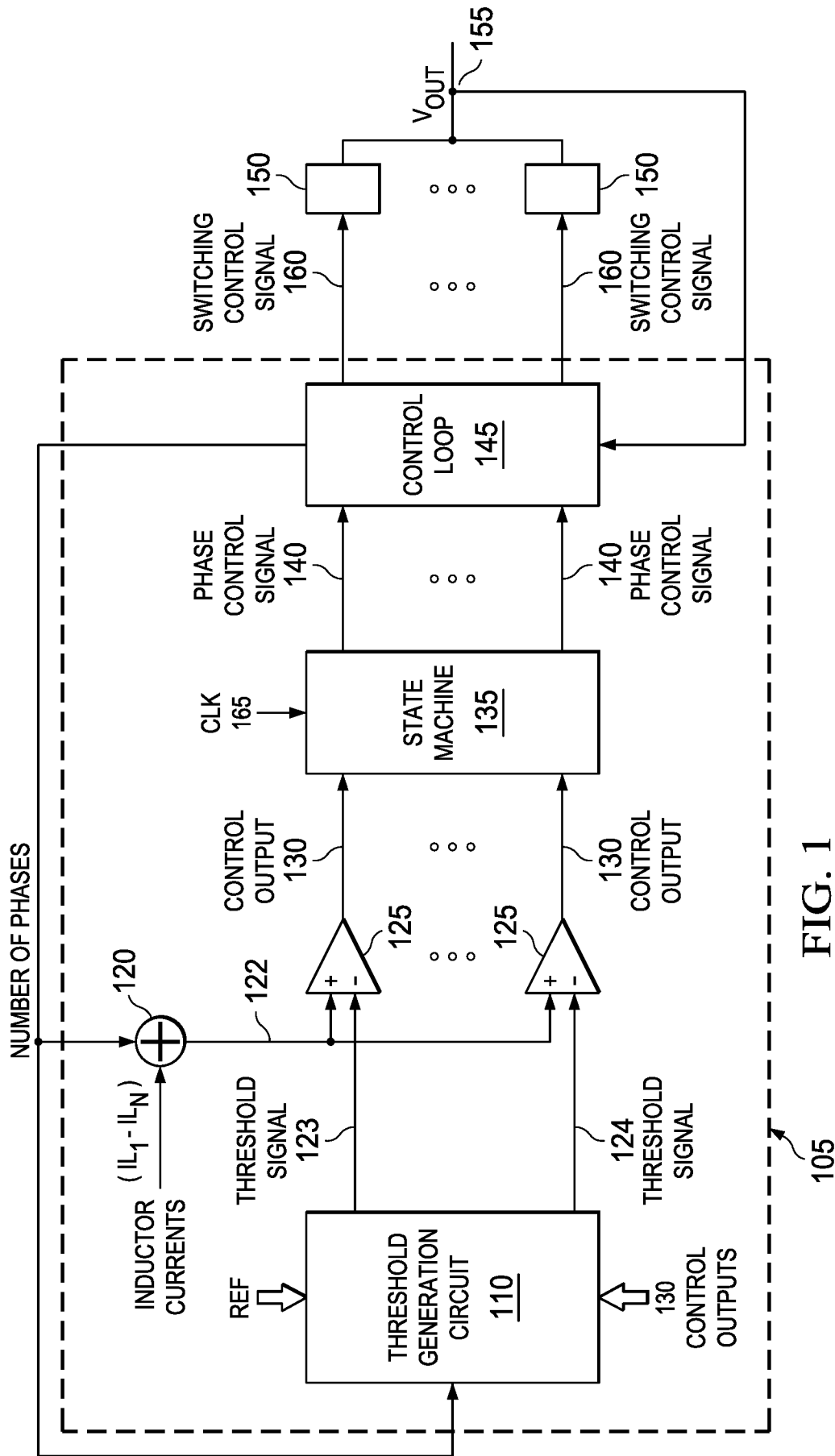
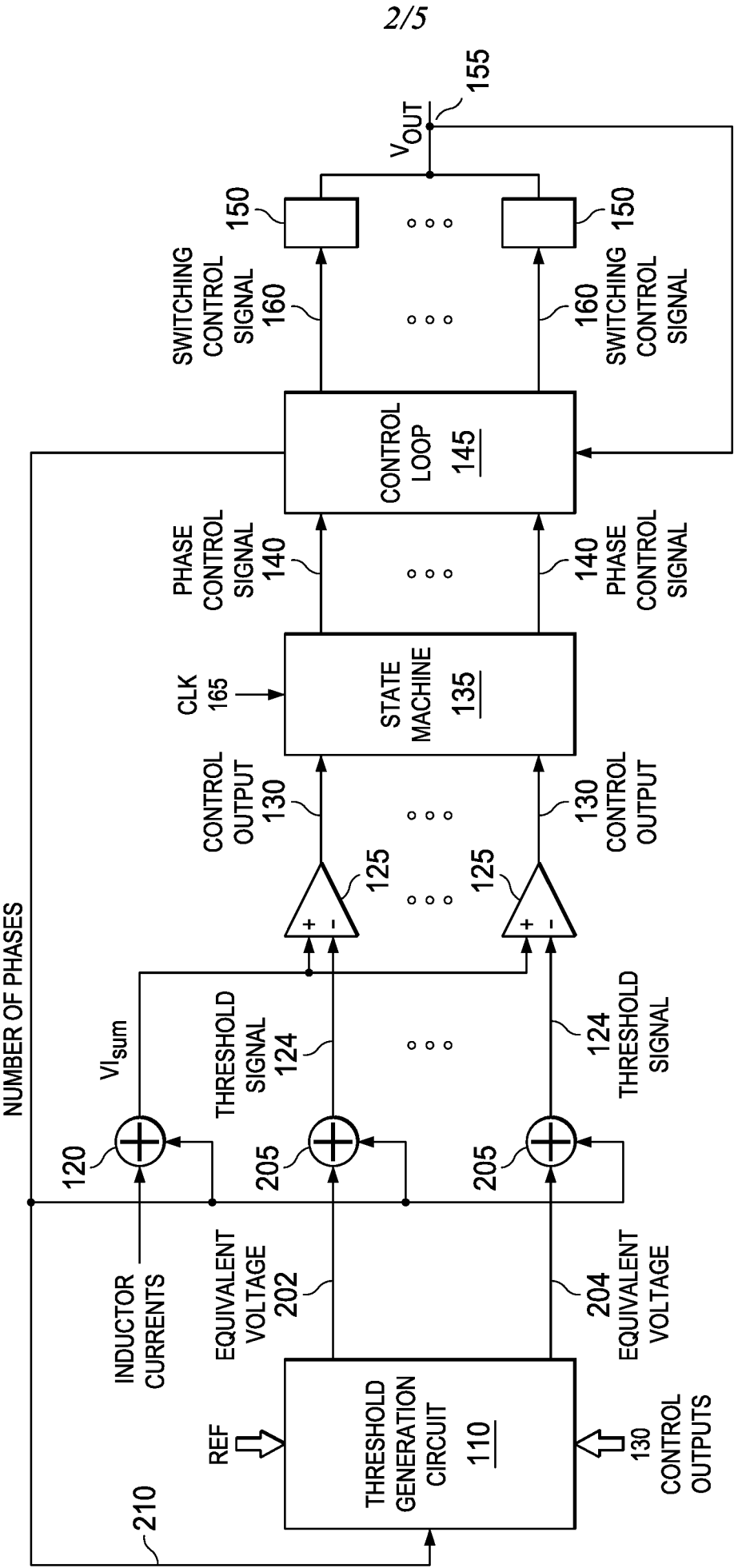


FIG. 1



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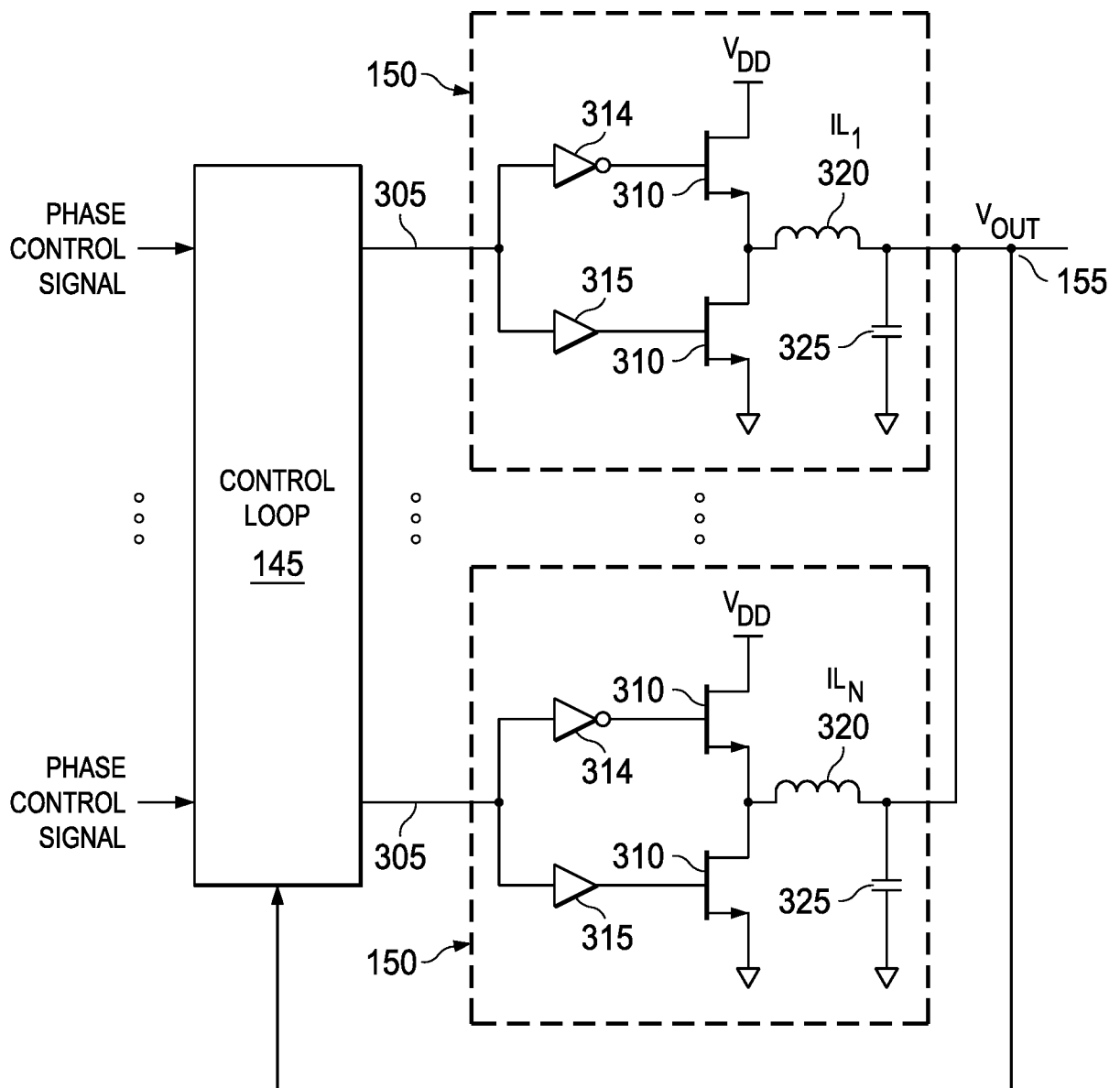


FIG. 3

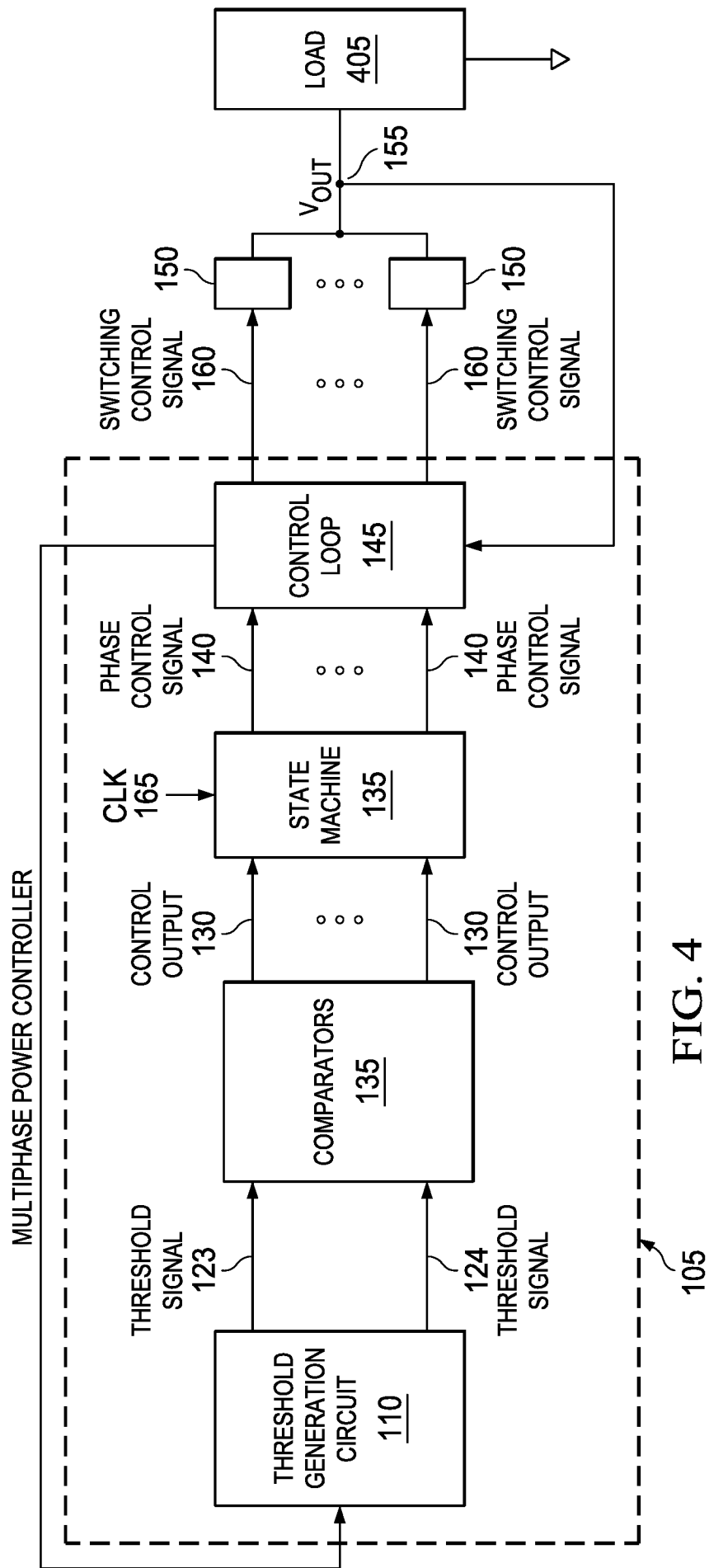


FIG. 4

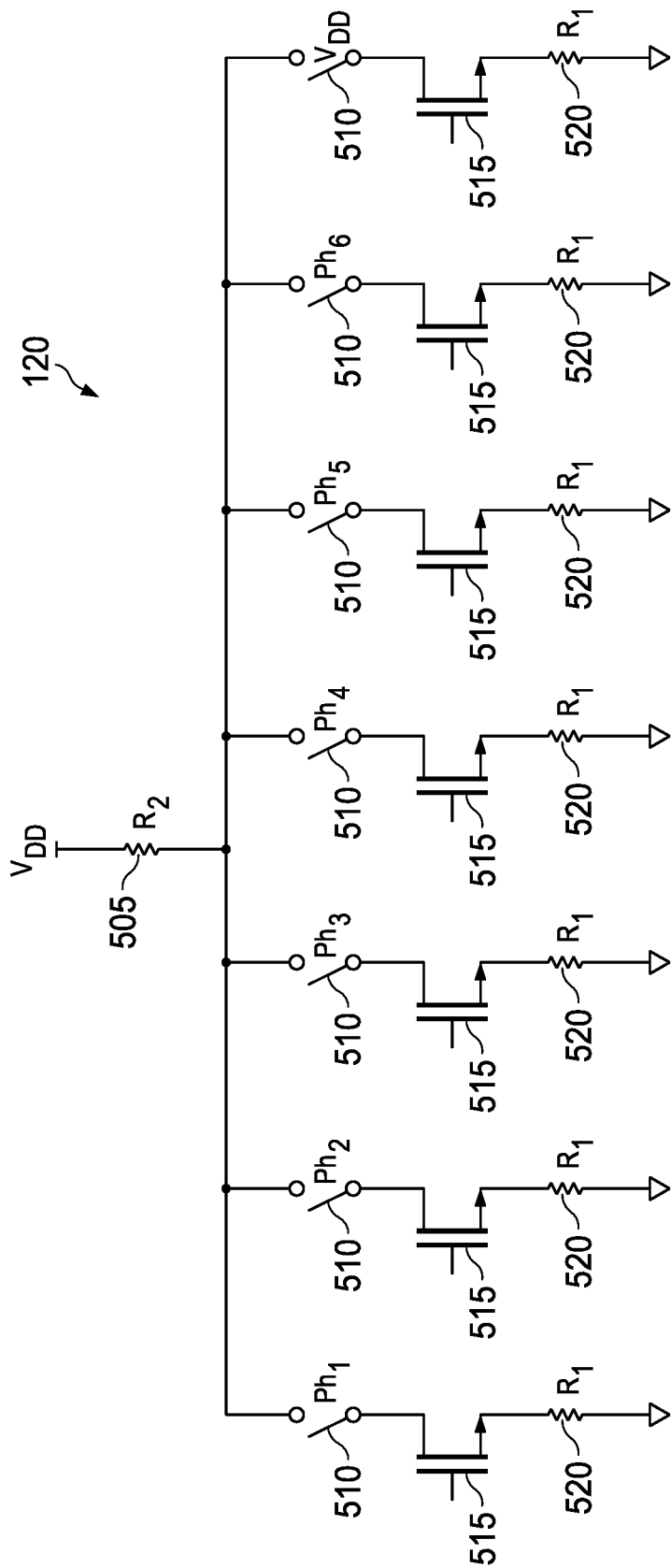


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2017/051670

A. CLASSIFICATION OF SUBJECT MATTER		
G05F 1/56 (2006.01) G05F 1/40 (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)		
G05F 1/00-1/575, H02M 3/00-3/02		
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, Information Retrieval System of FIPS		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/0200274 A1 (INFINEON TECHNOLOGIES AUSTRIA AG.) 09.08.2012, paragraphs [0016], [0018]-[0019], [0021]-[0022], [0027], [0031] [0032], [0061]-[0064], [0067], [0069]-[0072], [0076], [0080]-[0084], [0091]-[0093], [0108]	1-19
A	US 2006/0012351 A1 (INTERSIL AMERICAS, INC.) 19.01.2006	1-19
A	US 2006/0255778 A1 (INTERSIL AMERICAS, INC.) 16.11.2006	1-19
A	US 8541995 B2 (INFINEON TECHNOLOGIES AUSTRIA AG.) 24.09.2013	1-19
A	US 2006/0152205 A1 (BENJAMIM TANG et al) 13.07.2006	1-19
☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
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Date of the actual completion of the international search		Date of mailing of the international search report
15 December 2017 (15.12.2017)		21 December 2017 (21.12.2017)
Name and mailing address of the ISA/RU: Federal Institute of Industrial Property, Berezhkovskaya nab., 30-1, Moscow, G-59, GSP-3, Russia, 125993 Facsimile No: (8-495) 531-63-18, (8-499) 243-33-37		Authorized officer I. Belikov Telephone No. (495) 531-64-81