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SCHWEITZER ENGINEERING LABORATORIES, INC. [US/US]; 2350 Ne Hopkins Court, Pullman, WA 99163 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **DONOLO, Marcos, A.** [US/US]; 150 Nw Terre View Dr H39, Pullman, WA 99163 (US). **GUZMAN-CASILLAS, Armando** [US/US]; 305 Sw Prairie Street, Pullman, WA 9916 (US).

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(54) Title: DISTRIBUTED BUS DIFFERENTIAL PROTECTION USING TIME-STAMPED DATA

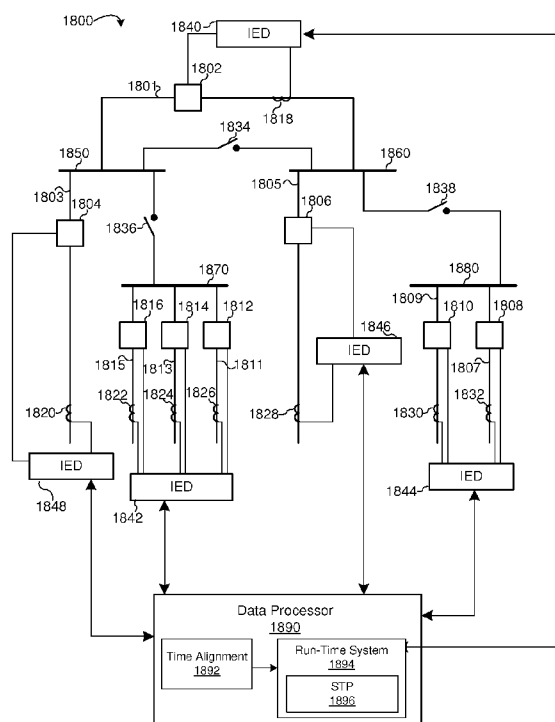


Figure 18

(57) Abstract: A distributed busbar protection system using time-stamped data gathered from measurement devices in an electrical power system bus arrangement by respective intelligent electronic devices (IEDs). The IEDs may derive the timestamp information from a clock or other time source, which may be synchronized to a common time source and/or an absolute time. The time-stamped measurement data may be used by a protection device to monitor and/or protect the electrical power system. The protection device may include a real-time vector processor, which may time-align the time-stamped data, determine one or more bus differential protection zones, and implement a differential protection function within each of the protection zones. One or more protective control signals may be transmitted to the IEDs to trip the corresponding breakers and clear the bus fault.



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TITLE

DISTRIBUTED BUS DIFFERENTIAL PROTECTION USING TIME-STAMPED DATA

TECHNICAL FIELD

5 **[0001]** This disclosure relates to bus differential protection and, in particular, to using time-stamped data for distributed bus differential protection.

BRIEF DESCRIPTION OF THE DRAWINGS

10 **[0002]** Additional aspects and advantages will be apparent from the following detailed description of preferred embodiments, which proceeds with reference to the accompanying drawings, wherein:

[0003] Figure 1 is a block diagram of one embodiment of a substation state and topology processor in communication with a substation, electrical power system network;

15 **[0004]** Figure 2A is a block diagram of an embodiment of a substation, electrical power system network;

[0005] Figure 2B depicts an embodiment of branch input data structure;

[0006] Figure 2C depicts an embodiment of a node input list data structure;

[0007] Figure 3 is a data flow diagram of one embodiment of a substation state and topology processor;

20 **[0008]** Figure 4 is a block diagram of a substation state and topology processor;

[0009] Figure 5 is a block diagram of a state and topology processor;

[0010] Figure 6 is a block diagram of a substation, electrical power system network;

[0011] Figure 7A is a flow diagram of a method for processing merged branches in a current branch-to-node data structure;

25 **[0012]** Figure 7B is a flow diagram of a method for processing merged branches in a voltage branch-to-node data structure;

[0013] Figure 8A is a flow diagram of one embodiment of a method for generating a current node vector;

30 **[0014]** Figure 8B is a flow diagram of one embodiment of a method for generating a voltage node vector;

[0015] Figure 9 is a representation of a current and/or voltage node vector;

[0016] Figure 10 is a flow diagram of a method for monitoring a substation, electrical power system network using a current topology and a plurality of current measurements;

[0017] Figure 11 is a block diagram of a polarity convention;

[0018] Figure 12A is a flow diagram of a method for performing a current consistency check;

[0019] Figure 12B is a graphical depiction of a current and/or voltage consistency check;

[0020] Figure 13A is a flow diagram of a method for performing a Kirchhoff's Current Law and current measurement refinement;

[0021] Figure 13B is a block diagram of a portion of a substation, electrical power system network;

[0022] Figure 14 is a flow diagram of a method for performing a phase current unbalance check and symmetrical components check;

[0023] Figure 15 is a flow diagram of a method for performing a voltage consistency check, measurement refinement, and symmetrical components check;

[0024] Figure 16 depicts one embodiment of an application for visualizing a substation power system network;

[0025] Figure 17 depicts one embodiment of an application for visualizing measurement and/or alarm details;

[0026] Figure 18 depicts one embodiment of a power system comprising plural buses;

[0027] Figure 19 is a block diagram of a state and topology processor configured to provide distributed bus differential protection;

[0028] Figure 20 is a functional block diagram of one embodiment of a current differential element;

[0029] Figure 21 is a functional block diagram of one embodiment of an external fault detection logic module;

[0030] Figure 22 is a block diagram of a system for distributing a common time source and/or absolute time to distributed devices;

[0031] Figure 23 is a block diagram of a data processor; and,

[0032] Figure 24 is a flow diagram of one embodiment of a method for providing distributed bus differential protection.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0033] Figure 1 depicts an exemplary substation, electrical power system network (SEPSN) 100. The SEPSN 100 may comprise various elements used for electrical power transmission and/or power distribution. For example, the SEPSN 100 may

comprise a generator 110, which may be connected to a bus 120 via a circuit breaker 113. A load 117 may be connected to the bus 120 via a circuit breaker 115. As used herein, a circuit breaker (such as circuit breakers 113 and 115) may refer to any device capable of interrupting and/or altering an electric circuit and/or an electrical connection (such as a connection between generator 110 and load 117).

[0034] A bus 130 may be connected to bus 120 via power transmission line 132. A power transmission line 132 may comprise circuit breakers 133 and 135. A bus 140 may be connected to the bus 120 via a power transmission line 142. The power transmission line 142 may comprise circuit breakers 143, and 147.

[0035] One or more Intelligent Electronic Devices (IED) 150, 152, and 154 may be communicatively coupled to one or more elements of the SEPSN 100. As used herein, an IED may refer to any one or combination of a central processing unit (CPU)-based relay and/or protective relay, communication processor, digital fault recorder, phasor measurement unit (PMU), phasor measurement and control unit (PMCU), phasor data concentrator (PDC), relay with phasor measurement capabilities, or any other device capable of monitoring an electrical power system.

[0036] In the Figure 1 embodiment, a PMU 150 may be configured to measure or otherwise sample a signal (*e.g.*, a phase current and/or phase voltage waveform) on bus 120. The waveform may comprise a voltage and/or current waveform corresponding to one or more components of a three-phase system. Similarly, PMU 152 may be configured to sample a signal waveform present on bus 130, and PMU 154 may be configured to sample a signal waveform present on bus 140.

[0037] The PMUs 150, 152, and 154 may be configured to process sampled signal waveforms to calculate, for example, current and/or voltage phasors. The PMUs 150, 152, and 154 may read one or more correction factors (that may be input by the user) for modifying the magnitude and/or phase of a phasor measurement. As used herein, "measurement data" may refer to a phasor measurement of a sinusoidal signal. In some embodiments, measurement data may refer to a measurement of a three-phase, phase current and/or voltage signal (*e.g.*, a measurement may comprise three separate measurements of each phase of a three-phase system).

[0038] The PMUs 150, 152, and 154 may be configured to apply a timestamp to data. This may be done using any phasor measurement and/or timestamping technique and/or methodology known in the art, including, but not limited to the techniques and methods described in: U.S. Patent No. 6,662,124 entitled, "Protective

Relay with Synchronized Phasor Measurement Capability for Use in Electric Power Systems,” to Schweitzer, III et al.; U.S. Patent No. 6,845,333 entitled, “Protective Relay with Synchronized Phasor Measurement Capability for Use in Electric Power Systems,” to Anderson et al.; and U.S. Application Pub. No. 2007/0086134 entitled, “Apparatus and Method for Estimating Synchronized Phasors at Predetermined Times Referenced to an Absolute Time Standard in an Electrical System” to Zweigle et al., each of which is hereby incorporated by reference in its entirety.

[0039] The measurement data obtained by the PMUs 150, 152, and 154 may be communicated to a Data Processor (DP) 160. In addition, one or more of the PMUs 150, 152, and 154 may communicate dynamic topology data to the DP 160. This dynamic topology data may comprise the state of the circuit breakers and/or switches 113, 115, 133, 135, 143, 147 of the SEPSN 100, and the like. As used herein, the term “switch” may refer to a switch component, a disconnect switch, and/or a disconnect component. As will be discussed in additional detail below, dynamic topology data may be combined with static network topology data to generate an operating topology of the SEPSN 100. The static topology data may comprise information, such as: the number of nodes in the SEPSN 100, the connection between various nodes in the SEPSN 100, the measurements available for each node and/or branch in the SEPSN 100, phase current and/or voltage measurement correction factors, and the like.

[0040] As used herein, a “node” may refer to a bus, such as buses 120, 130, and 140 of the SEPSN 100, and a “branch,” as used herein, may refer to a path of conduction and/or connection between one or more nodes (*e.g.*, a power transmission line comprising zero or more circuit breakers or the like).

[0041] Elements 150, 152, and 154 may comprise IEDs, such as PMUs and/or PMCUs, which may be configured to gather measurement data and dynamic topology data for transmission to DP 160. This data may comprise, but is not limited to: one or more phase current measurements on a branch and/or voltage measurements on a node 120, 130, and/or 140; the status of circuit breakers and/or disconnect switches 113, 115, 133, 135, 143, 147; the quality status of these circuit breakers and/or disconnect switches; and the like.

[0042] The DP 160 may comprise configuration data including one or more user-defined thresholds. These user-defined thresholds may be used in one or more monitoring functions of the DP 160. For example, the DP 160 may receive phase measurements and dynamic topology data from PMUs 150, 152, and 154. The DP 160

may use this data to evaluate and/or monitor the state of the SEPSN 100. This monitoring may comprise comparing the received measurement and network topology data to the user-defined thresholds. The DP 160 may process the measurements received from the PMUs 150, 152, and 154 and may set one or more alarms

responsive to the processing. As will be discussed below, such alarms may include, but are not limited to: current and/or voltage consistency alarms; current and/or voltage unbalance alarms; current and/or voltage symmetrical component alarms; and the like.

[0043] Figure 2A depicts an embodiment of a SEPSN 200 (*e.g.*, substation, electrical power system network). The SEPSN 200 may comprise ten (10) nodes denoted N1 through N10. The SEPSN 200 may further comprise thirteen (13) branches denoted B1 through B13.

[0044] The SEPSN 200 may comprise one or more IEDs (elements IED1-IED5) communicatively coupled thereto. IED1 may be communicatively coupled to current transformers (CTs) CT1 and CT2. In this embodiment, IED1 may comprise a PMU and/or PMCU or a relay. CT1 and CT2 may be used to obtain current measurements on branches in the SEPSN 200. Although not shown in Figure 2A, one or more voltage transformers may be used to obtain phase voltage measurements on one or more of the nodes (N1-N10) of the SEPSN 200. The CT1 may measure a current between N1 and N4, and CT 2 may measure a current from N3 to N4, and so on. The IEDs coupled to the SEPSN 200 may be in communication with branch elements of the SEPSN 200. For example, IED2 may be communicatively coupled to branch B1 and B2, and may be configured to detect the state of branch B1 and B2 (*e.g.*, whether the branches B1 and/or B2 are closed, and the like).

[0045] As depicted in Figure 2A, the SEPSN 200 may comprise a plurality of IEDs 1-5 monitoring one more aspects of the SEPSN 200, including topology data of the SEPSN 200 (*e.g.*, the state of branches B1-B11) and/or measurement data (*e.g.*, phase current measurements obtained by current transformers CT1-CT8). The data collected by the IEDs 1-5 may be transmitted to a state and topology processor (not shown) and made available to various protective and monitoring functions running thereon in one or more data structures. Various embodiments of such data structures are described below in conjunction with figures 2B and 2C.

[0046] In one embodiment, two data structures may be used to describe the SEPSN 200, a branch input list data structure (shown in Figure 2B) and a node input list data structure (shown in Figure 2C).

[0047] The branch input list data structure may comprise information about a branch in a SEPSN 200 (*e.g.*, branches B1-B11 in Figure 2A). The branch input list data structure may comprise an entry for each branch in the network, and each entry may comprise data describing the branch. As such, the branch input list data structure may

5 comprise:

- 1) The number of branches in the SEPSN 200 (*e.g.*, 11 branches in Figure 2A)
- 2) A branch input data structure for each branch, comprising:

- a) A FROM node identifier;
- b) A TO node identifier;
- 10 c) Branch Closed Status (whether the branch is closed)
- d) Branch Close Status Quality (whether the branch close status is good)
- e) Number of current measurements on the branch

- f) A-Phase measurements

- 15 i) Current measurements
- ii) Current correction factors

- g) B-Phase measurements

- i) Current measurements
- ii) Current correction factors

- 20 h) C-Phase measurements

- i) Current measurements
- ii) Current correction factors

- i) Threshold data

- i) Current consistency threshold

- 25 ii) Current unbalance threshold

- iii) Positive, negative, and zero sequence overcurrent threshold

- 3) KCL threshold

[0048] Figure 2B depicts one embodiment 210 of data structure 220, comprising a

30 branch input list data structure 230 corresponding to the SEPSN 200 of Figure 2A. Although Figures 2B and 2C depict tree data structures 210, one skilled in the art would recognize that any data organization technique and/or methodology known in the art could be used under the teachings of this disclosure, and as such, this disclosure should not be read as limited to any particular data structure type.

[0049] A top-level node 220 of the tree data structure 210 may be labeled INPUT_DATA. The INPUT_DATA node 220 may be configured to contain a branch list 230, which comprises one or more branch input list data structures 240 described above. Additionally, the INPUT_DATA node 220 may comprise a “list_of_nodes” entry (not shown), which will be described in detail below in conjunction with Figure 2C.

[0050] The “list_of_branches” entry 230 may comprise a “number_of_branches” entry 232 indicating the number of branches in the SEPSN (*e.g.*, in the SEPSN 200 depicted in Figure 2A, the “number_of_branches = 11”) and one or more branch input list instances 240. Each node of the SEPSN 200 depicted in Figure 2A may have a corresponding branch instance 240 (*e.g.*, a branch input list instance 240 for each of the eleven (11) branches in SEPSN 200).

[0051] Branch three (3) (B3 in Figure 2A) may be described by branch instance 250. Branch instance 250 may comprise one or more child instances defining the branch configuration, the branch state, phase-current measurements on the branch, phase-current correction factors, and one or more user-defined threshold values. For example, a “from_node” 251 may identify the source node of the branch (and a “to_node” 252 may identify a destination node of the branch to accurately reflect the topology of the SEPSN 200; referring back to Figure 2A, branch 3 (B3) is coupled to nodes N4 and N3).

[0052] Referring again to Figure 2B, the “closed” instance 254 and the “closed_status_quality” instance 255 may indicate that branch (B3) is closed and that the closed quality status is good.

[0053] The “number_of_current_measurements” instance 256 may indicate the number of measurements available on the branch (*e.g.*, two (2) measurements for branch B3). Referring again to Figure 2A, branch B3 comprises two CTs (CT2 and CT3) communicatively coupled thereto.

[0054] The “branch” instance 250 may comprise one or more phase-current measurements and phase-current correction factors 260, 270, and 280 associated with the branch 250. An “A_phase” instance 260 may comprise the A phase current measurements and correction factors of the branch 250. A “B_phase” instance 270 may comprise the B phase current measurements and correction factors of branch 3 250. And a “C_phase” instance 280 may comprise the C phase current measurements and correction factors of branch three (3) 250.

[0055] Each phase measurement/correction factor instance 260, 270, and 280 may comprise a current measurement instance (*e.g.*, instance 261) and a correction factor instance (*e.g.*, instance 263) for each current measurement on the branch. For example, in Figure 2B, instance 256 indicates that branch 3 250 comprises two (2) current measurements. As such, the A_phase current measurement instance 261 may comprise two (2) A phase current measurements instances 261.1 and 261.2 under instance 261 and two (2) A phase current correction factors 263.1 and 263.2 under current correction factor instance 263.

[0056] A “current_measurement” instance 261.1 may comprise a measured current magnitude measurement 261.1A, and a “current_phase_measurement” instance 261.1.B may comprise a corresponding phase measurement. The current measurement instance 261.2 may comprise similar measurements (not shown).

[0057] The “current_correction_factor” instance 263 may comprise a first current correction factor 263.1 associated with the first current measurement instance 261.1.

The “current_correction_factor[1]” instance 263 may comprise child instances 263.1A and 263.1B defining a magnitude correction factor 263.1A and a phase-angle correction factor 263.1B. The use of correction factors 263.1 and 263.2 are discussed in more detail below. The “current_correction_factor[2]” instance 263.2 may comprise current correction factors for current measurement 2, 261.2.

[0058] The B_phase instance 270 and the C_phase instance 280 may each comprise one or more current measurements (not shown) and current correction factors (not shown) for the B and C phases of a three-phase current system, respectively.

[0059] The branch instance 250 may comprise one or more user defined constants 257. As discussed above, a branch constant 257 may comprise a current consistency threshold 257.1, a current unbalance threshold 257.2, and a positive, negative, and zero sequence overcurrent threshold. The use of constants 257 is described in more detail below.

[0060] The “INPUT_DATA” instance 210 may further comprise a “node_input_list” (not shown in Figure 2B), which may comprise data describing one or more nodes in a SEPSN (*e.g.*, SEPSN 200 of Figure 2A). As such, the “node_input_list” entry may comprise a sub-entry for each node in the network, and each sub-entry therein may comprise data describing the node and any phase voltage measurements thereon. In one embodiment, a node input list structure may comprise:

- 1) Number of nodes in the SEPSN 200 (*e.g.*, 10)

2) A node_input_data structure for each node, comprising:

- a) KCL node information
- b) A-Phase measurements at the node
 - i) Number of voltage measurements
 - ii) Voltage measurements
 - iii) Voltage correction factors
- c) B-Phase measurements at the node
 - i) Number of voltage measurements
 - ii) Voltage measurements
 - iii) Voltage correction factors
- d) C-Phase measurements at the node
 - i) Number of voltage measurements
 - ii) Voltage measurements
 - iii) Voltage correction factors
- e) Positive -sequence undervoltage threshold
- f) Negative-sequence overvoltage threshold
- g) Zero-sequence overvoltage threshold

[0061] Figure 2C depicts one embodiment of a data structure 210 comprising a “node_list” instance 235. As discussed above, the “INPUT_DATA” instance 220 may comprise a “list_of_branches” instance 230 containing data describing one or more branches in a SEPSN. The “INPUT_DATA” node 220 may further comprise a “list_of_nodes” instance 235, which may comprise a “number_of_nodes” instance 247, indicating the number of nodes in the SEPSN. A container instance 249 may comprise a data structure corresponding to each node in the SEPSN. For example, in the SEPSN of Figure 2A, the container instance 249 may comprise ten (10) instances 265, one for each node in the network 200.

[0062] A node instance 265 may comprise a KCL instance 271, which may indicate whether the node is suitable for KCL check. As will be discussed below, a node may be suitable for KCL check if all of the branches reaching the node are accounted for in the substation model. In addition, as will be discussed below, a KCL check may be possible where all the nodes in a particular node group are KCL nodes, and all the branches leaving the group of nodes are metered.

[0063] The node instance 265 may further comprise an “A_phase” instance 273 comprising a “number_of_voltage_measurements” instance 274 and a voltage measurement instance 275. The voltage measurement instance 275 may comprise one or more A phase voltage measurement instances 275.1. The

5 “voltage_measurement” instance 275.1 may comprise an A phase magnitude 275.1A and A phase angle 275.1B. Although not shown in Figure 2C, a B_phase instance 283 and a C_phase instance 293 may comprise similar voltage measurement nodes.

[0064] A_phase instance 275 may further comprise a “voltage_correction_factor” instance 277, which may comprise one or more correction factor instances 277.1. The
10 correction factor instance 277.1 may comprise magnitude 277.1A and phase 277.1B correction factors associated with the voltage measurement 275.1. The use of correction factors 275.1 is described in more detail below. Although not shown in Figure 2C, the B_phase instance 283 and the C_phase instance 293 may comprise similar voltage correction factors.

15 **[0065]** The “node[1]” instance 265 may comprise one or more user-defined thresholds 295. As discussed above, the user-defined thresholds 295 may comprise a positive-sequence undervoltage threshold, a negative-sequence overvoltage threshold, and/or a zero-sequence overvoltage threshold. The use of the user-defined thresholds 295 is discussed in more detail below.

20 **[0066]** Figure 3 depicts a data flow diagram 300 of one embodiment of a State and Topology Processor (STP) 360. As shown in Figure 3, the STP 360 may receive a static topology data input 354, a dynamic topology data input 355, and measurement data input 356. In response to these inputs, the STP 360 may output refined measurements 361 and alarms 362. The dynamic topology data may include data such
25 as breaker status, switch status, and the like.

[0067] As described above in conjunction with Figures 2A-2C, the static topology data 354 may comprise a data structure, such as input list data structure 210 of Figures 2B and 2C, describing a topology of a SEPSN. The static topology may be input into the STP 360 from an external storage location. Alternatively, the STP may comprise
30 data storage means (*e.g.*, memory, disk, or the like) for storing the static topology data 354. The static topology data 354 may comprise data describing: the nodes in the SEPSN; the branches in the SEPSN; the number of phase current and/or phase voltage measurements available on each node and/or branch; phase voltage and/or current measurement correction factors; and the like.

[0068] The STP 360 may receive dynamic topology data 355. The dynamic topology data 355 may comprise data relating to the status of one or more circuit breakers, switches, conductors, conduits, or the like in a SEPSN. As discussed above, the dynamic topology data 355 may be obtained by one or more IEDs and/or PMUs (not shown) communicatively coupled one or more components of the SEPSN. As dynamic topology data 355 is received by the STP 360, the dynamic topology may be used along with the static topology 354 to determine an operating topology of the SEPSN. The operating topology may be embodied as a data structure, such as the tree data structured discussed above in conjunction with Figures 2B and 2C. For example, dynamic topology data 355 may comprise data relating to the state of closed branches 254 and/or closed_status_quality node 255 in Figure 2B.

[0069] STP 360 may receive measurement data 356. Measurement data 356 may comprise one or more phase current and/or phase voltage measurements obtained by one or more IEDs, PMUs and/or PMCUs (now shown) communicatively coupled to the SEPSN. As discussed above, the phase voltage and/or current measurements 356 (as well as the dynamic topology data 355) may comprise timestamp information to allow the STP 360 to time align the measurements to a common time standard.

[0070] Upon receiving inputs 354, 355, and 356, the STP 360 may be configured to produce one or more normalized and/or refined phase current and/or phase voltage measurements 361. These refined measurements may be used in protective and/or monitoring functions of the SEPSN (not shown). In addition, STP 360 may produce one or more alarms 362. The alarms 362 may be produced if one or more measurements 354, 355, 356, and/or derivatives thereof exceed or otherwise fall outside of one or more user-defined operating thresholds of STP 360 (*e.g.*, thresholds 257 of Figure 2B and/or thresholds 295 of Figure 2C).

[0071] Turning now to Figure 4, a block diagram 400 of one embodiment of a Data Processor (DP) 420 is depicted. DP 420 may be communicatively coupled to one or more IEDs, such as relays, phasor measurement and control units (PMCU) and/or phasor measurement units (PMU) 401 or relays and 416 located within and/or communicatively coupled to a SEPSN. In Figure 4, The DP 420 is depicted as communicatively coupled to sixteen (16) PNCUs labeled PMCU_401-PMCU_416. The PMCU_401-416 may be configured to communicate with the DP 420 using a communication standard, such as the IEEE C37.118 standard (hereafter "118 standard"). The 118 standard is a standard for synchronized phasor measurement

systems in power systems. The 118 standard is not media dependent and, as such, may be used on EIA-232 and Ethernet communications connections. Accordingly, PMCU_401-416 and DP 420 may be referred to as "118 devices" configured to interact with the PMCU_401-416 using the 118 standard. One skilled in the art, however, would
5 recognize that the PMCU_401-416 and the DP 420 could be configured to use any communications standard and/or protocol known in the art. As such, this disclosure should not be read as limited to any particular communications standard and/or protocol. For instance, in some embodiments, the PMUs 410 through 416 may be communicatively coupled to the DP 420 via Fast Message protocol or the like.

10 **[0072]** The PMCU_401-416 may provide measurement data and/or network topology data to the DP 420. This data may comprise timestamp information according to the 118 standard, or some other time alignment technique. The messages transmitted by the PMCU_401-416 may comprise time stamping information (*e.g.*, may comprise synchrophasors transmitted according to the 118 standard). The time
15 alignment module 430 may time align such messages using the time stamping information.

[0073] Alternatively, in some embodiments, the time alignment module 430 may time align messages from the PMCU_401-416 to a common time reference (not shown), which may provide a common time reference to the DP 420, the PMCU_401-
20 16 communicatively thereto, and/or to other IEDs communicatively coupled to the DP 420. The common time reference (not shown) may be provided by various time sources including, but not limited to: a Global Positioning System (GPS); a radio time source, such as the short-wave WWV transmitter operated by the National Institute of Standards and Technology (NIST) at 2.5 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz,
25 or a low frequency transmitter, such as WWVB operated by NIST at 60 Hz; a cesium clock; an atomic clock; over an IEEE-1588 time-over-Ethernet system; and the like. The time alignment module 430 may modify the magnitude and/or phase of phase measurements received from the PMCU_401-416 to conform to the common time reference (not shown) and/or the PMCU_401-416 may be configured to modify one or
30 more of a magnitude and/or phase measurement to align the measurement to the common time reference (not shown). In addition, in some embodiments, the time alignment module 430 may comprise a buffer memory or other buffering means to time align incoming messages from the PMCU_401-416. However, as discussed above, in the Figure 4 embodiment, a time reference (not shown) may not be required since the

messages themselves may comprise time alignment information (*e.g.*, the messages transmitted by the PMCU_401-416 may comprise synchrophasors or the like).

[0074] A super packet maker module 440 may receive the time-aligned measurement and dynamic topology data from time alignment module 430, and may generate a single composite packet comprising the time-aligned data received from PMCU_401-416. The super packet maker 440 may be configured to communicate with the time alignment module using the 118 standard.

[0075] The super packet maker 440 may transmit the packet comprising the time-aligned phasor measurement and/or topology data to Run Time System (RTS) 450. In one embodiment, the super packet maker module 440 may transmit the composite packet to RTS 450 using the 118 standard. In this embodiment, the RTS 450 may comprise a 118 protocol gateway module 452, which may be configured to communicate with the super packet maker module 440 using the 118 protocol. In other embodiments, other protocols and/or communications infrastructures may be used in place of the 118 protocol, including, but not limited to: the IEEE 1344 standard; BPA PDCStream; IEC 61850; OPC-DA / OPC-HAD; Internet Protocol (IP); Transmission Control Protocol (TCP); TPC/IP; User Datagram Protocol (UDP); or the like. As such, this disclosure should not be read as limited to any particular communication protocol, communication standard, and/or communication infrastructure.

[0076] The RTS 450 may make the time-aligned phase current and/or phase voltage measurements and dynamic topology data received from PMCUs 01-16 401-416 available to a state and topology processor (STP) 460. In addition, the RTS 450 may comprise a data storage module 454, which may be used to store static network topology information relating to the SEPSN monitored by the system and/or PMCU_401-416. The STP 460 may be communicatively coupled to a data storage module 454, and may be configured to load network topology data therefrom. The network topology data stored in the data storage module 454 may comprise a data structure, such as an input list data structure depicted in Figures 2B and 2C (*e.g.*, input list data structure 210), and may include a static topology of the monitored SEPSN. In this embodiment, the STP 460 may be configured to load the data structure from storage module 454, and to then update the structure with the phase-current and/or voltage measurements and dynamic topology data (*e.g.*, status of circuit breakers, switches, and the like) received from the PMCUs 01-16.

[0077] The STP 460 may access the static and dynamic topology data to refine the received measurements and to perform one or more protective functions and/or system checks. The operation of the STP 460 is described in more detail below.

[0078] A human-machine interface (HMI) module 470 may be communicatively coupled to the DP 420 and the STP 460. The HMI module 470 may be configured to display or otherwise make available to a human operator the refined current measurements, the refined phase voltage measurements, and/or alarms (if any) produced by the STP 460. Accordingly, the HMI module 470 may comprise a user interface or other display means to display of the state of the electrical power system to a user.

[0079] A local PMCU 480 may be communicatively coupled to the STP 460 and may be configured to receive the refined measurements and/or alarms (if any) produced by the STP 460. The local PMCU 480 may be communicatively coupled (via a communications network supporting, for example, the 118 standard or some other protocol) to an external device 485. The external device 485 may be an IED or other device configured to communicate with the PMCU 480. The external device 485 may be capable of configuring and/or controlling one or more components of the SEPSN (e.g., open and/or close one or more circuit breakers and/or switches, remove and/or add one or more loads or the like). Responsive to the refined measurements and/or alarms generated by the STP 460, the local PMCU 480 may cause the device 485 to reconfigure and/or control the SEPSN to thereby provide protection and/or additional control services to the SEPSN. For example, the external device 485 may be configured to send an alarm indicating undesired operating conditions, cause a circuit breaker to open and/or close, a load to be shed, or the like.

[0080] As discussed above, the STP 460 outputs station topology, refined measurements, measurement alarms, unbalanced currents and sequence quantities to the Run Time System 450, including the local PMCU 480 and a user programmable task module 490. The user programmable task module 490 may comprise one or more pre-configured and/or user programmable tasks. As such, the user programmable task module 490 may comprise an IEC 61131-3 compliant device (e.g., a programmable device that complies with the IEC 61131-3 standard). The tasks implemented on the user programmable task module 490 may use the data produced by the STP 460 to monitor the power system. For example, a bus differential protection module (not shown) may be implemented on the user programmable task module 490.

[0081] Figure 5 is a block diagram of one embodiment of a state and topology Processor (STP) 560. The STP may receive inputs 562 from a run time engine, such as the Run Time System 450 discussed above.

[0082] The STP 560 may comprise a topology processor 570, which may receive branch input data 572. The branch input data 572 may be derived from the static and dynamic topology data discussed above. As such, the branch input data 572 may reflect a state of a SEPSN, and as such, may comprise a combination of static SEPSN configuration data and dynamic SEPSN data. As used herein, the combination of static and dynamic topology data generated by the topology processor 570 may be referred to as an "operating topology" of a SEPSN.

[0083] The topology processor 570 may use branch input data 572 to generate a current topology 582 and a voltage topology 592. Jointly, the current topology 582 and the voltage topology 592 may comprise an operating topology of the SEPSN. The current topology 582 feeds a current processor 580 and the voltage topology 592 feeds a voltage processor 590.

[0084] The topology processor 570 may merge network nodes to create node groups according to the closed status of the branches within topology data 572. To create the current topology 582, the topology processor 570 may merge nodes when the non-metered branches are closed or when the branch closed status quality of the branch is false. To create the voltage topology 592, topology processor 570 may merge nodes when branches are closed. A more detailed description of current topology 582 and voltage topology 592 are provided below.

[0085] The current processor 580 may receive the current topology 582, node data 573, and current measurements 584 and produce outputs 585, which may comprise refined current measurements 585.1, current unbalance conditions 585.3, and sequence currents 585.4. In addition, current processor 580 may provide user-defined alarms 585.2 for current unbalance and symmetrical component conditions. Systems and methods for generating outputs 585 are described in additional detail below.

[0086] The voltage processor 590 may receive the voltage topology 592, node data 573, and voltage measurements 594 and produce outputs 595, which may comprise refined voltage measurements 595.1 and sequence voltages 595.3. In addition, the voltage processor 590 may provide user-defined alarms 595.2 for voltage symmetrical component conditions, measurement consistency. Systems and methods for generating outputs 595 are provided below.

[0087] As discussed above, the topology processor 570 may use branch input data 572 (comprising the static topology and the dynamic topology data) to generate an operating topology of the SEPSN comprising a current topology 582 and a voltage topology 592.

5 **[0088]** The current topology may comprise the list of groups of nodes and the branch to node list. The nodes inside every group of nodes are connected by closed branches that have no current measurements. The branches to node list may specify which metered closed branches connect which group of nodes.

10 **[0089]** The voltage topology may comprise a list of groups of nodes and a branches to node list. The nodes inside every group of nodes are connected by closed branches (with or without current measurements). The branches to node list may specify which open branches with closed status quality equal to false connect which groups of nodes.

15 **[0090]** Turning now to Figure 6, an exemplary SEPSN 600 is depicted to illustrate one embodiment of a node merging process. The network 600 may comprise eleven (11) nodes (denoted N6.1 through N6.11), seven terminal nodes (N6.5 – N6.11) (where KCL=FALSE), eight metered branches (BR6.1 through BR6.8) as such, branches BR6.1 through BR6.8 may comprise a current transformer, and three (3) non-metered branches (BR6.9 through BR6.11). Nodes N6.1, N6.2, N6.3 and N6.4 may comprise a voltage transformer (respectively VT6.1, VT6.2, VT6.3, and VT6.4) attached and/or
20 communicatively coupled thereto to measure a voltage on Nodes N6.1 through N6.4.

[0091] When all merging switches of Figure 6 are open (*e.g.*, branches BR6.9-11 are open as shown in Figure 9), the current processor branch-to-node data may be represented by table 1 below:

	BR6.1	BR6.2	BR6.3	BR6.4	BR6.5	BR6.6	BR6.7	BR6.8	BR6.9	BR6.10	BR6.11
From Node ID	N6.1	N6.1	N6.2	N6.2	N6.2	N6.3	N6.4	N6.4	N6.1	N6.1	N6.3
To Node ID	N6.5	N6.3	N6.6	N6.7	N6.8	N6.9	N6.10	N6.11	N6.3	N6.2	N6.4

Table 1

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[0092] Nodes in the current topology branch-to-node data may be merged when a non-metered branch is closed or when the branch close status quality of the non-metered branch is FALSE. After a non-metered branch closes (or its close status quality is FALSE), the topology processor may replace all instances of the non-metered

branch TO node identifier with the FROM node identifier in the branch-to-node data array. The TO node identifier and FROM node identifier may be defined in a structure, such as data structure 210, discussed above in conjunction with Figure 2B.

[0093] In the Figure 6 example, the dynamic topology data 572 associated with the SEPSN 600 may indicate that branch 10 (BR6.10) has closed. Referring back to Figure 2B, this may be indicated in the input data 210 structure as setting element 254 to TRUE and/or element 255 close status quality indicator to FALSE for the branch. Closing branch BR6.10 may merge nodes N6.1 and N6.2. As such, the branch-to-node data of Table 1 may be updated as shown in Table 2, such that the TO node ID of the merged branch (BR6.2) is replaced by the FROM node ID of the merged branch:

	BR6.1	BR6.2	BR6.3	BR6.4	BR6.5	BR6.6	BR6.7	BR6.8	BR6.9	BR6.10	BR6.11
From Node ID	N6.1	N6.1	N6.1	N6.1	N6.1	N6.3	N6.4	N6.4	N6.1	N6.1	N6.3
To Node ID	N6.5	N6.3	N6.6	N6.7	N6.8	N6.9	N6.10	N6.11	N6.3	N6.1	N6.4

Table 2

[0094] As shown in Table 2, the FROM node ID of BR6.3-BR6.5 has been changed from N6.2 to N6.1 and the TO node ID of BR6.10 has been changed from N6.2 to N6.1.

[0095] Using the branch-to-node data, the topology processor 570 may generate groups of nodes for consistency checks and/or current refinement. Table 3 may represent a group of nodes and branch list generated from Table 2 for current topology 582:

Group of Nodes for Current Topology	Branch List
N6.1, N6.2	BR6.1, BR6.2, BR6.3, BR6.4, BR6.5
N6.3	BR6.2, BR6.6
N6.4	BR6.7, BR6.8

Table 3

[0096] In Table 3, BR6.10 is omitted since the FROM node and TO node of BR6.10 are the same (see table 2).

[0097] Like the current topology branch-to-node data, the voltage topology branch-to-node data may comprise branch to node interconnection information. As discussed above, this information may be determined by evaluating static and dynamic topology data. For the purposes of the voltage topology branch-to-node data, the topology processor 570 may merge a branch if the branch status is closed (*e.g.*, element 254 of Figure 2B) and the close status quality indicator is TRUE for the branch (*e.g.*, element 255 of Figure 2B).

[0098] A voltage branch-to-node data for the SEPSN 600, before closing branch BR6.2, is provided in Table 4:

	BR6.1	BR6.2	BR6.3	BR6.4	BR6.5	BR6.6	BR6.7	BR6.8	BR6.9	BR6.10	BR6.11
From	N6.1	N6.1	N6.2	N6.2	N6.2	N6.3	N6.4	N6.4	N6.1	N6.1	N6.3
To	N6.5	N6.3	N6.6	N6.7	N6.8	N6.9	N6.10	N6.11	N6.3	N6.2	N6.4

Table 4

[0099] After closing Branch BR6.2, the topology processor may merge nodes N6.1 and N6.3, and all instances of the branch TO node may be replaced with the FROM node ID in the voltage branch-to-node data array. This change is reflected in the updated voltage branch-to-node data of Table 5:

	BR6.1	BR6.2	BR6.3	BR6.4	BR6.5	BR6.6	BR6.7	BR6.8	BR6.9	BR6.10	BR6.11
From	N6.1	N6.1	N6.2	N6.2	N6.2	N6.1	N6.4	N6.4	N6.1	N6.1	N6.1
To	N6.5	N6.1	N6.6	N6.7	N6.8	N6.9	N6.10	N6.11	N6.1	N6.2	N6.4

Table 5

[00100] In Table 5, all references to node 3 (N6.3) have been replaced with the merged node 1 (N6.1), including the TO node IDs in branches 2 and 9 (BR6.2, BR6.9) and the FROM node IDs in branch 6 and 11 (BR6.6, BR6.11).

[00101] Using the voltage branch-to-node data of table 5, the topology processor 570 may generate groups of nodes for voltage consistency checks and/or voltage measurement refinement. Table 6 may represent a voltage node group generated from Table 5:

Group of Nodes for Voltage Topology
N6.1, N6.3
N6.2
N6.4

Table 6

[00102] In Table 6, only nodes having voltage measurements thereon may be included (*e.g.*, only node IDs N6.1-N6.4). Nodes 1 and 3 (N6.1, N6.3) are in the same group, since after closing branch 9 (BR6.2), these nodes may be at a common voltage level.

[00103] Figure 7A is a flow diagram of one embodiment of a method 700 for processing merged branches in a current processor branch-to-node data structure. At step 710, a branch-to-node data array may be obtained. Step 710 may comprise accessing the topology data (*e.g.*, the input 572 of Figure 5). At step 720, the topology data may be used to initialize a current processor branch-to-node data array. As discussed above, the current processor branch-to-node data of step 720 may be initialized by analyzing static and dynamic topology data to determine the state of the interconnections therein. The result of step 720 may be one or more branch-to-node data arrays as depicted in tables 1, 2, and 3.

[00104] At step 730, method 700 may loop through every non-metering branch defined in the current topology branch-to-node data array obtained at step 720. At step 740, the merged status of a branch may be determined. As discussed above, for a current branch-to-node data, a branch may be merged if the topology data indicates that the branch is closed (*e.g.*, element 254 of Figure 2B, "closed" node has value TRUE) and/or the closed quality status is false (*e.g.*, element 255 of Figure 2B, "closed_quality_status").

[00105] At step 750, the branch-to-node data structure may be updated to reflect the merged status of the branch. As discussed above, this may comprise replacing all instances of the TO node ID in the merged branch with the FROM node ID in the current branch-to-node data structure.

[00106] At step 760, method 700 may determine whether all the branches in the branch-to-node data have been processed per steps 740-750. If not, the flow may continue at step 740 where the next branch in the current processor branch-to-node data may be processed; otherwise, the flow may terminate at step 770.

[00107] Figure 7B is a flow diagram of one embodiment of a process 701 for merging nodes in a voltage processor branch-to-node data structure. Process 701 may be substantially the same as process 700 discussed above in conjunction with Figure 7A with the exception of step 741 (740 in Figure 7A).

[00108] At step 741, a branch in the voltage branch-to-node data, may be merged if the topology data indicates that the branch is closed (*e.g.*, element 254 of Figure 2B, “closed” node has a value of TRUE) and/or the closed quality status is true (*e.g.*, element 255 of Figure 2B, “closed_quality_status”). If step 741 determines that the branch is merged, the flow may continue to step 751; otherwise, the flow may continue to step 761. After determining the status of each branch in the voltage processor branch-to-node array substantially as described above, the flow may terminate at step 771.

[00109] After initializing and processing the current branch-to-node data and the voltage branch-to-node data, the topology processor 570 may create one or more node groups of nodes (*e.g.*, groups such as the current topology group of table 3 and the voltage topology group of table 6).

[00110] The current group(s) may be based upon the current branch-to-node data structure and may comprise group(s) with current measurements on every branch leaving the group. A current processor module (*e.g.*, current processor module 580 of Figure 5) may use these group(s) to perform current consistency checks, KCL check, measurement refinement, and the like.

[00111] The voltage group(s) may be based upon the voltage branch-to-node data structure and may comprise group(s) of nodes. A voltage processor module (*e.g.*, voltage processor module 590 of Figure 5) may use these group(s) to perform voltage consistency checks, measurement refinement, and the like.

[00112] The current group(s) may be formed from a current node vector. In a current node vector, nodes may be grouped by whether they have been “merged” with one or more other nodes in the array. For example, if a particular node (*e.g.*, node X) is merged into a branch (it is the TO node ID of a merged branch), the number of nodes associated with node X may be zero (0). If node X is by itself (*e.g.*, not merged, nor has any nodes merged therein), the number of nodes associated with node X may be one (1). If other nodes are merged into node X (*e.g.*, it is the FROM node ID of a merged branch), the number of nodes associated with node X may be the number of merged nodes plus one (1).

[00113] Similarly, the voltage group(s) may be formed from a voltage node vector. In the voltage node vector, nodes may be grouped by whether they have been “merged” with one or more other nodes in the array. For example, as above, if a particular node (*e.g.*, node Y) is merged with another node due to a closed branch (it is the TO node of

a merged branch), the number of nodes associated with node Y may be zero (0). If the node Y is by itself (*e.g.*, not merged into another node, nor has any nodes merged therein), the number of nodes associated with node Y may be one (1). If other nodes are merged into node Y (*e.g.*, it is the FROM node of a merged branch), the number of nodes associated with node Y may be the number of merged nodes plus one (1).

[00114] Figure 8 is a flow diagram of one embodiment of a method 800 for generating a current node vector. At step 810, the node vector may be initialized from SEPSN topology data (static and/or dynamic) and a current branch-to-node data structure may be obtained. In one embodiment, the input data received at step 810 may comprise a current branch-to-node data array produced by method 700 of Figure 7A.

[00115] At step 815, each node in the topology may be processed (*e.g.*, steps 820 through 835 may be performed on each node in the topology), and at step 820, each branch in the branch-to-node data arrays may be processed (*e.g.*, steps 825 through 830 may be performed for each branch).

[00116] At step 825, process 800 may determine if the TO node ID and the FROM node ID in the branch being processed are the same as the current node (*e.g.*, if the node was merged per process 700 of Figure 7A). If so, the flow may continue to step 830; otherwise, the flow may continue to step 835.

[00117] At step 830, the TO ID and the FROM ID branch nodes may be added to a current node vector (or any other data structure capable of holding a number of entries), which may contain nodes belonging to the same group (hereafter current node vector). The current node vector may comprise one or more pointers (or other data references) to the nodes comprising the group. The current node vector may comprise a counter indicating the number of nodes in a particular entry. Accordingly, at step 830, the counter may be incremented if necessary.

[00118] At step 835, method 800 may determine whether there are additional branches to process. If so, the flow may continue to step 820; otherwise, the flow may continue to step 840. At step 840, method 800 may determine whether there are additional nodes to process. If so, the flow may continue to step 815; otherwise, the flow may continue to step 845.

[00119] At step 845, method 800 may again iterate over all of the nodes in the topology (*e.g.*, may perform steps 850 through 860 on each node). At step 850, process 800 may determine whether the node is in the current node vector (*e.g.*, linked to and/or referenced by an entry in the current node vector). If the node is in the

current node vector, the flow may continue to step 860; otherwise, the flow may continue to step 855.

[00120] At step 855, the node may be added to the current node vector. This step may be required where the node is “by itself”. As such, at step 855, the node may be added to a new node vector comprising only the node itself.

[00121] At step 860, process 800 may determine whether there are additional nodes to process. If so, the flow may continue at step 845 where the next node may be processed; otherwise, the flow may terminate at step 865.

[00122] As described above, method 800 of Figure 8 may be used to generate a current node vector. In addition, method 800 may generate a voltage node vector. These vectors may be generated separately (*e.g.*, in separate iterations of method 800) or concurrently (*e.g.*, in the same iteration of method 800).

[00123] Figure 8B is a flow diagram of a method 801 for generating a voltage node vector. Method 801 may be performed substantially as described above: at step 811, a voltage node vector may be initialized; at step 816, method 801 may iterate over all of the nodes in the topology; at step 821, each branch in the voltage branch-to-node data structure may be processed; and, at step 826, each node is compared to each branch in the voltage branch-to-node data structure. At step 826, the node ID may be compared to the TO node ID and the From node ID in the voltage branch-to-node data structure. If the condition of step 826 is true (the node ID matches the TO node ID and the FROM node ID), the flow continues to step 831 where the node is added to the voltage node vector; otherwise, the flow continues to step 836.

[00124] After processing each node over steps 821-841, the flow continues to step 846 where each node in the topology is processed. At step 851, method 801 determines whether the node is in the voltage node vector. If not, the flow continues to step 856 where the node is added to the voltage node vector substantially as described above; otherwise, the flow continues to step 861 where the next node is processed.

[00125] Referring again to Figure 5, the topology processor 570 may perform an embodiment of methods 700 and 800 on the topology data included in branch input data 572. The result may be a current branch-to-node data structure, a voltage branch-to-node data structure, a current node vector, and a voltage node vector. Applying process 800 to the SEPSN 600 depicted in Figure 6, and current branch-to-node data structure depicted in Table 2, may result in a node vector 900 depicted in Figure 9.

[00126] Figure 9 depicts exemplary data structures 900 as processed by a topology processor (*e.g.*, topology processor 570 of Figure 5). A data structure 903 may represent a current branch-to-node data structure corresponding to the SEPSN depicted in Figure 6. As such, data structure 903 may represent an equivalent set of data as depicted in Table 1. Data structure 903 is replicated in Figure 9 to allow for a better depiction of the current node vector 910. The data structure 905 may represent a current branch-to-node data structure after merging branch 10 (*e.g.*, BR6.10 of Figure 6). Data structure 905 may represent an equivalent set of data as depicted in Table 2. Data structure 905 is replicated in Figure 9 to allow for a better depiction of the current node vector 910.

[00127] As discussed above, the current topology branch-to-node data 903 may represent the current-branch topology of the SEPSN 600 of Figure 6 before closing branch BR6.10. After merging branch BR6.10, references to the merged node 2 (N6.2) may be replaced with node 1 (N6.1). The current branch-to-node data 905 depicts an update to the branch-to-node data reflecting this change. In the updated current branch-to-node data 905, references to node 2 (N6.2) in branch 3-5 (BR6.3 – BR6.5) have been replaced with references to node 1 (N6.1). In addition, the TO node ID in branch 10 (BR6.10) has been changed to node 1 (N6.1).

[00128] The current node vector 910 depicts one embodiment of a current node vector structure 910 corresponding to branch-to-node data structures 903 and 905. The current node vector 910 may be formed by applying an embodiment of method 800, depicted in Figure 8, to the topology of Figure 6 and its corresponding current branch-to-node data 905.

[00129] The current node vector 910 comprises a group node listing 920. The group node list 920 comprises a group entry (*e.g.*, G.1) for each node in the topology. The group node list 920 depicted in Figure 9 corresponds to a SEPSN having eleven (11) nodes, as such, the group node list 920 comprises eleven (11) group entries 920. Each entry G.1 through G.11 in the group list 920 comprises: a group identifier; the number of nodes in the group; and a pointer or other reference into a node vector 940. For example, group G.1 may comprise a group identifier “1” G.1A, the number of nodes in the group G.1B (two (2)), and a reference G.1C to the node vector 940.

[00130] After merging branch 10 (B6.10) in the SEPSN 600 of Figure 6, a group comprising node 1 (N6.1) and node 2 (N6.2) may be formed. This may be reflected by group 1 (G.1) of the current node vector 910. Group G.1 may be identified as group 1

at entry G.1A. Entry G.1B may indicate that there are two (2) nodes comprising group 1. Entry G.1C may comprise a pointer or other reference into node vector 940. The reference of G.1C may point to the first node in the group (*i.e.*, node 1 (N6.1)). Using the reference of G.1C and the number of nodes indicator G.1B, the nodes comprising the group can be determined by traversing node vector G.1B two (2) times. As such, group G.1 may comprise nodes demarcated by 940.1, N6.1, and N6.2. Although 910 is depicted as using an array-based relative offset addressing and/or referencing scheme, one skilled in the art would recognize that any data reference scheme could be used under the teachings of this disclosure. As such, this disclosure should not be read as limited to any particular data structure 910 format and/or data referencing technique.

[00131] As discussed above, a group whose node has been merged into another group may comprise zero (0) nodes. Group two (2) G.2 is such a group. This is because in the Figure 9 embodiment, node 2 (N6.2) has been merged into group 1 (G.1) with the closing of branch 10 (BR6.10). As such, the number of nodes in group G.2 is zero and the reference into the reference vector may be zero (0) and/or null.

[00132] As discussed above, a group may comprise a single node. Groups G.3 through G.11 are such groups. Accordingly, G.11 comprises one (1) node (N6.11) and points to the node vector location comprising node eleven (11) (N6.11) in node vector 940.

[00133] A voltage node vector may be generated using data structures substantially equivalent to data structures 903, 905, 910, and 940 depicted in Figure 9.

[00134] Referring again to Figure 5, the topology processor 570 may produce an operating topology of the SEPSN comprising a current topology 582 for the current processor 580. The current topology 582 may comprise a current branch-to-node data array, and a current node vector, and associated node vector. The current processor 580 may also receive current measurements 584. As discussed above, the current measurements 584 may be obtained by one or more PMUs (not shown) and/or PMCUs or relay (not shown) disposed within a substation power system network, the current measurements 584 may be time-aligned substantially as described above. Also as discussed above, the current topology data 582 and current measurements 584 may be input to the current processor 580 as a tree structure (*e.g.*, the branch input list 220 described in conjunction with Figure 2B).

[00135] Upon receiving current topology data 582 and current measurement data 584, the current processor 580 may be configured to *inter alia*, scale each current

measurement by its corresponding correction factor, perform a consistency check on the current measurements, and refine the measurements. Figure 10 depicts a flow diagram of one embodiment of a method 1000 for performing these functions.

[00136] Turning now to Figure 10, at step 1010, method 1000 may receive a current topology, which, as discussed above, may comprise a current topology of the SEPSN (e.g., comprise a current branch-to-node data, etc.). In addition, the method 1000 may receive one or more current measurements associated with the current topology.

[00137] At step 1020, one or more correction factors may be read. The correction factors read at step 1020 may be read from the topology data discussed above. The correction factors may be used to normalize the current measurements with respect to the topology data received at step 1010. Figure 11 depicts one embodiment of a SEPSN topology that may be used to illustrate the use of one or more current correction factors at step 1020.

[00138] Turning now to Figure 11, node 1110 may be in electrical communication with node 1120 via a power transmission conductor 1130 to allow a current I_{1132} to flow therebetween. An IED 1112, such as a PMU and/or PMCU or relay, may be communicatively coupled to transmission conductor 1130 at or near node 1110 to measure a current I_{1112} thereon. Another IED 1122, which may be an IED, relay, a PMU and/or PMCU, may be communicatively coupled to transmission conductor 1130 at or near node 1120 to measure a current I_{1122} thereon. Given the polarities of IED 1112 and 1122, and assuming nonexistent and/or negligible measurement error, the measured currents I_{1112} and I_{1122} be the additive inverse of one another as shown in Equation 1.1:

$$\mathbf{[00139] \quad } I_{1112} = -I_{1122} = I_{1132} \qquad \text{Eq. 1.1}$$

[00140] Given Equation 1.1, a first measurement correction factor for the measurement obtained at IED 1112, k_1 may be 1 at 0° since the current flowing from node 1110 to node 1120 may cause a secondary current to enter IED 1112. Similarly, a second measurement correction factor for the measurement obtained at IED 1122, k_2 may be 1 at 180° (i.e., -1) since the primary current 1132 flowing from node 1110 to node 1120 may cause a secondary current to leave IED 1122. Using these correction factors, Equation 1.1 may be rewritten as shown in Equation 1.2:

$$\mathbf{[00141] \quad } k_1 I_{1112} = k_2 I_{1122}, \{k_1 = 1, k_2 = -1\} \qquad \text{Eq. 1.2}$$

[00142] The current correction factors discussed above may also be adapted to take into account properties of the device (e.g., current transformer) used to obtain the

current measurement. For example, a current correction factor may account for a turn ratio of the current transformer and/or IED used to obtain a current measurement (*e.g.*, 1112 and/or 1122 of Figure 11). Similarly, a current correction factor may address any phase shifting introduced by the current transformer and/or IED. This may allow the current correction factor to normalize measurements obtained by different current transformer types and/or configurations. As such, a current correction factor may comprise a magnitude correction factor and/or a phase correction factor. The magnitude and/or phase component of a particular current correction factor may be derived from any of the current measurement properties discussed above including, but not limited to: an orientation of the current measurement in a current topology; a current magnitude adjustment (*e.g.*, due to current transformer turn ratio or the like); a current phase adjustment (*e.g.*, due to current transformer phase shift); combinations thereof; and the like.

[00143] Voltage correction factors may be used to normalize voltage measurements obtained by the IEDs (*e.g.*, IED 1112 and/or 1122 of Figure 11). Like the current correction factors discussed above, the voltage correction factors may be used to address voltage measurement differences introduced by the transformer and/or IED used to obtain the measurements (*e.g.*, magnitude, phase shift, and the like). Voltage correction factors may also be used to address the orientation of voltage measurements in a voltage topology (*e.g.*, account for the polarity of a voltage measurement and the like). In addition, a voltage correction factor may address a voltage base value of a measurement (*e.g.*, the measurement may be taken relative to a voltage base).

[00144] Referring again to Figure 10, at step 1020, method 1000 may read and/or otherwise determine correction factors for every current measurement received at step 1010. In one embodiment, the correction factors may be static, such that they only need to be read or determined once. In other embodiments, one or more factors may be recalculated as the topology of the SEPSN changes (*e.g.*, in response to dynamic topology data). Alternatively, correction factors associated with one or more measurements may be user supplied and stored in data structure, such as data structure 210 of Figure 2B (*e.g.*, element 263 of Figure 2B). After determining the relevant current correction factors, the flow may continue to step 1030.

[00145] At step 1030, the current measurements received at step 1010 may be scaled (*e.g.*, normalized) using the correction factors of step 1020. The scaled current

measurements may be stored in a data structure for use in subsequent steps (*e.g.*, steps 1040-1060) of method 1000. The flow may then continue to step 1040.

[00146] At step 1040, method 1000 may perform a current measurement consistency check on the scaled current measurements. One embodiment of a method to perform such a check is described below in conjunction with Figures 12A and B. The flow may then continue to step 1050.

[00147] At step 1050, method 1000 may refine one or more of the current measurements. One embodiment of a method for refining current measurements is described below in conjunction with Figures 13A and 13B. The flow may then continue to step 1060.

[00148] At step 1060, method 1000 may perform current unbalance and symmetrical component checks. One embodiment of a method for performing these checks is described below in conjunction with Figure 14. The flow may then terminate at step 1070.

[00149] Figure 12A is a flow diagram of one embodiment of a method 1200 for performing a current consistency check. At step 1210, topology data and one or more scaled current measurements may be received. This data may be provided by an output of method 1100 described above in conjunction with Figure 11.

[00150] At step 1220, method 1200 may iterate each branch and phase within the topology data received at step 1210. As such, method 1200 may perform steps 1230 through 1280 for each branch and phase within the topology data of step 1210.

[00151] At step 1230, method 1200 may determine whether current measurements are available for the branch. This information may be provided in the topology data of step 1210 (*e.g.*, `number_of_current_measurements` entry 256 of Figure 2B). If there are measurements available in the branch, the flow may continue to step 1240; otherwise, the flow may continue to step 1280.

[00152] At step 1240, one or more scaled current measurements associated with the branch may be obtained. The scaled current measurements of step 1240 may be made available by another process (*e.g.*, process 1100 described above in conjunction with Figure 11) or may be computed at step 1240 given one or more correction factors provided in the topology data of step 1210.

[00153] At step 1250, a current measurement median may be determined. This may comprise computing the median value from the available current measurements. In an alternative embodiment, step 1250 may use the average value.

[00154] At step 1260, a consistency check may be performed on each of the current measurements for the current branch. This consistency check may comprise calculating a difference between each current measurement for the branch to the median measurement value of the branch (calculated at step 1250) against a consistency threshold value per Equation 1.4:

$$\mathbf{[00155] \quad |c_i - \gamma_B| < \varepsilon_B \quad \text{Eq. 1.4}}$$

[00156] In Equation 1.4, c_i may be a branch current measurement corresponding to one or more current phases, γ_B may be the median or mean current measurement for the branch and ε_B may be the consistency threshold for the phase and branch. If the inequality of Equation 1.4 is satisfied, the flow may continue to step 1280; otherwise, the flow may continue at step 1270.

[00157] At step 1270, a consistency alarm may be set indicating that one or more current measurements and/or phases of a current measurement fail to satisfy the consistency check of step 1260. The alarm may identify the branch, phase, and/or the one or more measurements that produced the inconsistency. The flow may continue to step 1280.

[00158] At step 1280, method 1200 may determine whether there are additional branches to process. If so, the flow may continue to step 1220; otherwise, the flow may terminate at step 1290.

[00159] Turning now to Figure 12B, a visual depiction of process 1200 is provided. In Figure 12B, measurements 1211 corresponding to a particular branch may be plotted on plot 1201, comprising an imaginary axis 1203 and a real axis 1205. A median value 1213 of the measurements 1211 may be determined. A consistency threshold associated with the phase and branch may be depicted as 1221. The radius of 1221 may correspond to the consistency threshold value. A measurement 1215 that differs from the mean and/or media value 1213 by more than a threshold 1221 may cause a consistency alarm to be asserted.

[00160] Turning now to Figure 13, one embodiment of a process 1300 for performing a KCL check and measurement refinement is depicted.

[00161] At step 1310, topology data and two (2) or more scaled current measurements may be received. The data received at step 1310 may be provided by an output of a method, such as 1100 described above in conjunction with Figure 11.

[00162] At step 1320, method 1300 may iterate over each node (e.g., each entry in a current merged node array) in the topology data received at step 1310. At step 1325,

method 1300 may iterate over each phase measurement available for the node and/or group of step 1320 (*e.g.*, each phase of a three-phase, phase current, or other signal measurement).

[00163] At step 1330, method 1300 may determine whether a KCL check may be performed on the node. In some embodiments, a KCL check may require that all currents reaching a node be available. This requirement may be imposed since method 1300 may operate under the axiom that the sum of currents reaching a node should be substantially zero (0) per Kirchhoff's Current Law (KCL). If one of the current measurements is unavailable, however, the KCL axiom may not hold, and as such, process 1300 may not yield meaningful results. Similarly, where the node is part of a node group (*e.g.*, as defined by the current node vector) a KCL check may be possible if all nodes in the group are KCL nodes (*e.g.*, have current measurements on their associated branches). If a KCL check can be performed on the node and/or node group, the flow may continue to step 1340; otherwise, the flow may continue to step 1380 where the next node and/or phase may be processed.

[00164] At step 1340, the scaled current measurements reaching the node may be summed and compared to a KCL threshold value per Equation 1.5:

$$\left| \sum_{i=1}^N c_i \right| < KCL_thre \quad \text{Eq. 1.5}$$

[00166] In Equation 1.5, N may be the number of branches reaching a particular node group, c_i may be a particular phase-current measurement, and KCL_thre may be the KCL threshold (*e.g.*, instance 231 of Figure 2B).

[00167] At step 1350, method 1300 may determine whether the inequality of Equation 1.5 is satisfied. If the inequality is satisfied (*i.e.*, the absolute value of the sum is less than the KCL threshold), the flow may continue to step 1360; otherwise, the flow may continue to step 1370 where the next node and/or phase may be processed.

[00168] At step 1360, the current measurements associated with the node may be flagged appropriately (*e.g.*, marked as satisfying the threshold of step 1340), and the flow may continue to step 1365 where the phase-current measurements may be refined.

[00169] At step 1365, the phase-current measurements may be refined. In one embodiment, refinement may comprise refining the measurements relative to an overall error metric e . In particular, the phase-current measurements may be refined such that the overall error e is minimized. One embodiment of an approach to minimizing error is described below in conjunction with Figure 13B.

[00170] Figure 13B depicts a segment 1301 of a SEPSN. The segment 1301 may comprise a node 1311 having three branches connected thereto, each comprising a scaled current measurement: 1313 (A_1), 1315 (A_2), and 1317 (A_3). The current measurements 1313, 1315, and 1317 may correspond to a single phase of a three-phase, current signal reaching the node 1311.

[00171] As discussed above, the threshold condition of node 1311 may be given as Equation 1.6:

$$\mathbf{[00172]} \quad \left| \sum_{i=1}^3 A_i \right| < KCL_thre \quad \text{Eq. 1.6}$$

[00173] To refine the measurements 1313, 1315, and 1317, the overall error ϵ may be calculated per Equation 1.7:

$$\mathbf{[00174]} \quad \epsilon = \left| \sum_{i=1}^3 I_i \right| + |I_1 - A_1| + |I_2 - A_2| + |I_3 - A_3| \quad \text{Eq. 1.7}$$

[00175] In Equation 1.7, I may represent the metered and/or refined phase-current measurements reaching node 1311. Accordingly, Equation 1.7 equally distributes any measurement error between the three current measurements 1313 (A_1), 1315 (A_2), and 1317 (A_3).

[00176] To obtain a solution to minimize ϵ , Equation 1.7 may be rewritten in matrix form as shown in Equation 1.8:

$$\mathbf{[00177]} \quad \left\| \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} - \begin{bmatrix} 0 \\ A_1 \\ A_2 \\ A_3 \end{bmatrix} \right\| = \epsilon \quad \text{Eq. 1.8}$$

[00178] In Equation 1.8, the problem becomes one of minimizing error ϵ . To do so, the pseudo inverse of the matrix of Equation 1.8 may be obtained, and Equation 1.8 may be rewritten as Equation 1.9:

$$\mathbf{[00179]} \quad \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} \frac{3}{4} & -\frac{1}{4} & -\frac{1}{4} \\ -\frac{1}{4} & \frac{3}{4} & -\frac{1}{4} \\ -\frac{1}{4} & -\frac{1}{4} & \frac{3}{4} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} \quad \text{Eq. 1.9}$$

[00180] The structure of Equation 1.9 may remain constant as the number of currents reaching the node (e.g., node 1311) changes. As such, an equation for each entry in the matrix of equation 1.9 may be determined per Equation 1.10:

$$[00181] \quad a_{i,j} = \begin{cases} n/(n+1), & \text{if } i = j \\ -1/(n+1), & \text{if } i \neq j \end{cases} \quad \text{Eq. 1.10}$$

[00182] In Equation 1.10, n may represent the number of currents reaching a particular node and i and j may be the indices of the matrix in Equation 1.9. As such, for node 1311 of Figure 13B, n may be three (3).

- 5 [00183] To refine the phase-current estimates, Equation 1.10 may be applied to obtain entries in the matrix of Equation 1.9, and then multiply the matrix by the measurement vector (*i.e.*, the A_{1-n} vector). A closed form may be written as Equation 1.11:

$$[00184] \quad I_i = A_i - \sum_{j=1}^n \frac{A_j}{n+1}, \quad i=1,2,\dots,n \quad \text{Eq. 1.11}$$

- 10 [00185] As such, at step 1365, Equation 1.11 may be applied to the phase-current measurements A_i to thereby obtain refined measurements I_i . The refined measurements may be output to a HMI interface (*e.g.*, output 585.1 in Figure 5 to an HMI 470 of Figure 4).

- [00186] At step 1370, method 1300 may determine whether there are remaining current phases to processes. If so, the flow may continue to step 1325 where a next set of phase-current measurements of a multi-phase current (*e.g.*, three (3)-phase current) may be processed; otherwise, the flow may continue to step 1380.

- [00187] At step 1380, method 1300 may determine whether there are remaining nodes to process. If so, the flow may continue to step 1320 where the next node and/or node group may be processed; otherwise, the flow may terminate at step 1390.

[00188] Turning now to Figure 14, a flow diagram of one embodiment of method for performing a current unbalance, symmetrical component check is depicted.

- [00189] At step 1410, topology data and one (1) or more scaled current measurements may be received. The data received at step 1410 may be provided by an output of a method, such as 1100 described above in conjunction with Figure 11.

- [00190] At step 1420, method 1400 may iterate over all of the branches in the topology data received at step 1410. At step 1430, method 1400 may determine whether all phase current measurements of the particular branch are available. If so, the flow may continue at step 1440; otherwise, the flow may continue at step 1480 where the next branch may be processed.

[00191] At step 1440, an unbalanced branch check may be performed. The check of step 1440 may comprise determining a reference current (I_{REF}) value, which, in some

embodiments, may be the median value of the phase current magnitudes at the branch. Alternatively, the I_{REF} may be an average value

[00192] At step 1450, a ratio of the magnitude of each phase (e.g., each phase of a three (3)-phase current) to the reference current I_{REF} may be calculated per equation 1.13:

$$[00193] \quad unb_A = \left| \frac{|I_A|}{I_{REF}} - 1 \right| \quad \text{Eq. 1.13}$$

[00194] In Equation 1.13, unb_A may be the magnitude of the ratio of a magnitude of the A phase current measurement (I_A) to the reference current, I_{REF} minus 1. Equation 1.13, may be used to calculate the unbalance for each current phase (e.g., phases A, B, and C of a three (3)-phase current). The unbalance of Equation 1.13 may be expressed in terms of a percentage as in Equation 1.14:

$$[00195] \quad unb_A = \left| \frac{|I_A|}{I_{REF}} - 1 \right| \cdot 100 \quad \text{Eq. 1.14}$$

[00196] At step 1460, each of the phase-current unbalances may be compared to a user-defined unbalance threshold value associated with the branch. The topology data received at step 1410 may include these threshold values (e.g., i_unb_thre element 257.2 of Figure 2B). If any of the phases exceeds its respective unbalance threshold, the flow may continue at step 1465; otherwise, the flow may continue to step 1470.

[00197] At step 1465, a current unbalance alarm may be set on the current measurement. The alarm of step 1465 may be set for all phases of a multi-phase current (e.g., three (3)-phase current) and/or only the phases that fail to satisfy the unbalance threshold of steps 1450. The flow may then continue to step 1470.

[00198] At step 1470, the symmetrical components (negative, positive, and zero) of the three-phase current may be calculated. At step 1473, the symmetrical components may be compared to the user-defined threshold values associated with the branch symmetrical components. The topology data received at step 1410 may include these threshold values (e.g., as one or more values in data structure 210 of Figure 2B). If one or more symmetrical components exceeds its associated threshold, the flow may continue to step 1475; otherwise, the flow may continue to step 1480.

[00199] At step 1475, the symmetrical component alarm(s) may be set on the current and branch. After setting the alarm, the flow may continue to step 1480.

[00200] At step 1480, the next unprocessed branch (if any) may be checked, and the flow may continue to step 1420. If no branches remain to be processed, the flow may terminate at step 1490.

[00201] Referring again to Figure 5, current processor 580 may perform method 700 (described above in conjunction with Figure 7), which may comprise applying one or more correction factors to current measurements 584, computing a current measurement mean or median for each branch, checking branch current consistency, refining current measurements, and checking current balance and symmetrical components as described in conjunction with Figures 8-14.

[00202] If current refinement is possible, current processor 580 may output refined current values 585.1. In addition, the checks mentioned above (*e.g.*, consistency, KCL, unbalance, etc.) may comprise setting an alarm relating to one or more checked current phases, currents, and/or branches. As such, after processing one or more alarms 585.2 may be output from current processor 580. As discussed above in conjunction with Figure 4, these alarms may be routed to a HMI module (*e.g.*, element 470 of Figure 4) and/or a local PMCU (*e.g.*, element 480). A HMI may display one or more alarms to an operator of the state and topology processor, and a local PMCU may use the alarm data to invoke one or more protective functions including, but not limited to: sending an alarm, tripping one or more circuit breakers, changing the configuration of one or more switches, removing and/or adding one or more loads, or the like.

[00203] Current unbalance percentage values calculated by current processor module 580 (*e.g.*, per method 1400 described above in conjunction with Figure 14) may be provided via output 585.3. In addition, symmetrical components associated with each branch current may be provided via output 585.4. These outputs, along with the refined measurements and alarms discussed above, may be made available to a HMI and/or local PMCU to provide monitoring and protection to a SEPSN.

[00204] The voltage processor module 590 of STP 560 may receive voltage measurement data 594 and voltage topology data 592 from the topology processor 570. As discussed above, this data may be conveyed via a data structure similar to the tree data structure described above in conjunction with Figures 2B and 2C. The voltage processor 590 may be configured to apply voltage correction factors to the voltage measurement data 594, calculate median phase-voltage measurement values at each node in topology data 592, perform one or more voltage consistency checks,

refine the voltage measurements 594, and perform symmetrical component analysis on voltage measurements 594.

[00205] Turning now to Figure 15, a flow diagram of one embodiment of a method 1500 for monitoring phase voltages in a SEPSN is depicted. A voltage processor module, such as voltage processor module 590 of Figure 5, may perform method 1500.

[00206] At step 1510, method 1500 may receive network topology data (*e.g.*, a node list data structure and/or voltage merged node group), and/or one or more phase voltage measurements. The topology and phase voltage measurement data may be conveyed in a data structure similar to the "input data" data structure described above in conjunction with Figures 2B and 2C.

[00207] At step 1520, method 1500 may iterate over all of the node groups in the topology data received at step 1510 (*e.g.*, all node groups in the merged group data structure).

[00208] At step 1525, one or more correction factors may be applied to the voltage measurements received at step 1510. The correction factors may be stored in the network topology data of step 1510 in, for example, voltage correction factors 277 of Figure 2C.

[00209] At step 1530, a median value for each phase-voltage measurement may be determined. In alternative embodiments, an average phase-voltage measurement may be calculated at step 1530.

[00210] At step 1540, a voltage consistency check may be performed. The voltage consistency check of step 1540 may be similar to the current consistency check described above in conjunction with Figure 12A. As such, the consistency check may comprise calculating a difference between each phase-voltage measurement of a particular node and/or node group to the median phase-voltage measurement calculated at step 1530. The consistency check of step 1540 may be performed for all phases of each phase voltage measurement available at a particular node group. At step 1540, if the difference between the measured voltage and the measurement median is greater than a user-defined threshold (*e.g.*, defined in data structure 210 described above in conjunction with Figures 2A-C), the flow may continue to step 1550; otherwise, the flow may continue to step 1560.

[00211] At step 1550, a voltage consistency alarm may be set. The alarm may identify the voltage phase, measurement, node, and/or node group corresponding to the alarm. The flow may then continue to step 1560.

[00212] At step 1560, the symmetrical components for each group and/or node phase-voltage measurement may be calculated. At step 1570, these components may be compared to corresponding user-defined symmetrical component threshold(s). These thresholds may be stored in the data received at step 1510 (*e.g.*, in an input data structure 210 described above in Figures 2B and 2C). If one or more components exceed its associated threshold, the flow may continue at step 1575; otherwise, the flow may continue to step 1580.

[00213] At step 1575, the symmetrical component alarms may be set. These alarms may identify the node and/or node group and/or the measurement producing the alarms. The flow may then continue to step 1580.

[00214] At step 1580, method 1500 may determine whether there are nodes and/or node groups remaining to process. If so, the flow may continue to step 1520 where the next node and/or node group may be processed; otherwise, the flow may terminate at step 1590.

[00215] Referring back to Figure 5, the voltage processor 590 may perform method 1500 (described above in conjunction with Figure 15), which may comprise applying one or more correction factors to voltage measurements 594, computing a voltage measurement median or mean for each node and/or node group, checking measurement consistency, and/or performing a symmetrical components check.

[00216] The checks discussed above (*e.g.*, consistency, symmetrical component, etc.) may comprise setting an alarm relating to one or more phase voltages on one or more node groups, voltages, nodes, and/or node groups. As such, after processing, one or more alarms 595.2 may be output from voltage processor 590. As discussed above, alarm(s) 595.2 may be routed to HMI module (*e.g.*, HMI 470 of Figure 4) for display to a user. In addition, the alarms may be routed to a local PMCU (*e.g.*, PMCU 480 of Figure 4), which may invoke one or more protective functions responsive to the alarm(s) 595.2. These protective functions may include, but are not limited to: sending an alarm, tripping one or more circuit breakers, changing the configuration of one or more switches, removing and/or adding one or more loads, or the like. Additionally, one or more symmetrical components corresponding to voltage measurements 594 may be output at 595.3.

[00217] Referring to Figure 4, the DP 420 may be communicatively coupled to a human machine interface (HMI) 470. As discussed above, the HMI 470 may be used to

display monitoring information to a user of the DP 420. Such information may comprise refined measurements, alarms, and the like.

[00218] Figure 16 depicts one embodiment of an visualization interface 1600. The visualization interface 1600 may be displayed within a computer display and/or

5 application 1610. The application 1610 may be executable on a general and/or special purpose computing device comprising a processor (not shown), input devices (not shown), such as a keyboard, mouse, or the like, data storage (not shown), such as a disc drive, memory, or the like, and one or more output devices (not shown), such as display, audio speakers, or the like. The application 1610 may be presented on the
10 display of the computing device (not shown) and may comprise custom and/or general purpose software communicatively coupled to a state and topology processor and/or time aligned data processor (*e.g.*, the DP 420 and/or STP 460 of Figure 4).

[00219] The application 1610 may be configured to display a portion of the substation power system network to which the STP is connected. The display of the power system
15 may be based upon topology data received from the DP and/or STP. In addition, the topology display may comprise the real-time operating topology as determined by the DP and/or STP. As such, the display may show the current state of one or more breakers, switches, and other connective components in the power system.

[00220] Although not shown in Figure 16, the topology display may further include
20 indications of one or more bus differential protection zones determined by the current processor. As will be discussed below, a bus differential protection zone may include one or more busbars or nodes, and may be used to provide distributed bus differential protection to the power system.

[00221] The application 1610 may display refined current and/or voltage
25 measurements 1622 and 1624 received from the DP and/or STP. Although Figure 16 depicts only two (2) such measurements displayed on the application 1610, one skilled in the art would recognize that any number of measurements could be displayed in the application 1610 according to the configuration of the STP and/or the power system network.

30 **[00222]** The refined measurements 1622 and 1624 may be obtained substantially as described above. For example, a refined current measurement may represent a combination of multiple current measurements as refined using an error minimization metric. Similarly, refined voltage measurements may comprise a median, average, and/or error minimized voltage measurements.

[00223] One or more alarms 1612, 1614, and/or 1616 may be displayed in the application 1610. The alarms displayed on one or more components of the electrical power system, such as electrical power system nodes (*e.g.*, N1, N2, and so on), electrical power system branches, bus bars, or the like.

5 **[00224]** The alarms 1612, 1614, and/or 1616 may be generated responsive to any one or more of the alarm conditions described above (*e.g.*, KCL, symmetrical components, unbalance, or the like). The alarms 1612, 1614, and/or 1616 may related to current conditions, voltage condition, branch conditions, or the like. In addition, one or more of the alarms 1612, 1614, and/or 1616 may be related to a busbar fault
10 detected by a distributed bus differential protection scheme discussed below.

[00225] In addition, electrical power system components and/or measurements thereon, which have been verified as working properly may be marked as shown in element 1632; element 1632 indicates that the state of the particular branch and/or the measurements received therefrom are correct.

15 **[00226]** The application 1610 may be selectable such that selection of a particular node, branch, and/or alarm may display detailed information relating to the respective component. For example, selection of the alarm 1616 on branch B3 may cause application 1610 to display details regarding the measurements and/or alarms associated with the branch B3. One example of such a display 1700 is provided in
20 Figure 17.

[00227] As shown in Figure 17, an application 1710 may display additional information relating to a particular component within the power system network displayed the application 1610. Figure 17 displays details related to a branch B3 shown in Figure 16.

25 **[00228]** The application 1710 may comprise a measurement consistency check 1720 component, which may display each of the measurements 1721 and 1723 available at the particular component. Each measurement 1721 and 1723 may comprise a three-current measurement 1722 and 1724. A refined current measurement may be displayed at 1726, which may comprise three-phase refined measurements 1727
30 and/or symmetrical components 1728 of the refined measurement.

[00229] The application 1710 may further display alarms 1732 associated with the particular component. In the Figure 17 embodiment, a KCL 1734 and unbalance alarm 1736 may be displayed. However, one skilled in the art would recognize that any number of alarms or other notices could be displayed within the application 1710. For

example, if the component displayed in the application 1710 were a bus bar or node, the alarms could comprise voltage consistency alarms or the like.

[00230] As shown in Figure 17, the KCL alarm may 1734 be shown as “OK” indicating that the measurements 1721 and 1723 satisfy KCL, and the unbalance alarm 1736 may indicate an unbalance condition at the branch. Similarly, the application 1710 may be adapted to display information relevant to a distributed bus differential protection scheme. For example, a display component may include a differential protection component 1742, which may provide a list 1744 of the busbars or nodes that are included in the protection zone and/or a list 1746 of the branches included in the protection zone. Additional protection zone information, such as restraining current values, operating current values, slope characteristic values, pickup current thresholds, and the like may also be included (not shown).

[00231] The systems and methods disclosed herein may be applied to provide distributed bus differential protection. In electrical power transmission and distribution networks, a bus (also referred to as a busbar or node) may provide a connection for electric power transmission, generation, and loads. If a fault occurs on a bus, all circuits supplying fault current may be required to trip in order to isolate the fault. Thus, a bus fault may result in extensive loss of service. In some embodiments, the electrical power system may be capable of dynamically modifying its configuration (*e.g.*, dynamically connecting/disconnecting power system components, such as buses or nodes). One example of such an arrangement is described below in conjunction with Figure 18. Monitoring and/or protecting a complex, dynamic bus arrangement may comprise determining, in real-time, one or more bus differential protection zones (also referred to as “protection zones”) within the arrangement. A current differential protection function may be provided within each of the protection zones.

[00232] Bus monitoring and protection may be increasingly difficult when the arrangement has many terminals and/or spans large distances. For example, although all the buses in a particular bus arrangement may be within the same switchyard, the IEDs that monitor and/or protect other buses in the arrangement may be located at great distances from one another, which may preclude a centralized monitoring system. Further, in some embodiments, the buses themselves may be situated at great distances from each other, as may the IEDs that are configured to protect and monitor the system. When several IEDs are involved in a common protection scheme, communicatively coupling the IEDs may require long communication paths and

complex communication arrangements. Moreover, an increasing number of terminals connected to each bus may create additional protection and monitoring requirements, which, in turn, may increase the complexity of the protection scheme due to the increased number of breakers monitored and/or controlled by the protection scheme.

5 **[00233]** A cohesive protection system spanning multiple IEDs may significantly increase the accuracy and performance of a distributed bus differential protection scheme. Figure 18 is a block diagram of one embodiment of an electrical power system 1800 comprising a data processor 1890 configured to provide distributed bus differential protection. In the Figure 18 example, a data processor 1890 is configured to
10 receive time-stamped measurement data from the IEDs 1840, 1842, 1844, 1846, and 1848 (referred to herein as the Figure 18 IEDs). The Figure 18 IEDs may be communicatively coupled to various portions of the power system 1800 and, as such, may be distributed at various locations therein. In some embodiments, the Figure 18 IEDs may be separated by significant distances from each other and/or the data
15 processor 1890.

[00234] Although not shown in Figure 18, the Figure 18 IEDs may be communicatively coupled to respective time sources (*e.g.*, a common time source). Therefore, the Figure 18 IEDs may be time synchronized to one another. Accordingly, time-stamps applied to measurement data acquired by the Figure 18 IEDs may be
20 consistent with one another (*e.g.*, may be capable of being time aligned as described above). One example of a scheme for distributing a common time source and/or synchronizing distributed IEDs, such as the Figure 18 IEDs, is described below in conjunction with Figure 22. As will be described below, the data processor 1890 may be configured to time-align the measurements received from the Figure 18 IEDs and to
25 implement a distributed bus differential protection scheme using the time-aligned measurement data.

[00235] As discussed above, a distributed bus differential protection scheme may implement dynamic zone selection to assign terminal current information to appropriate protection zones. The Figure 18 power system illustrates one example of a bus
30 arrangement capable of comprising a plurality of dynamic (*e.g.*, changing) bus differential protection zones. The power system 1800 includes four buses, including bus 1850, bus 1860, bus 1870, and bus 1880. One or more protection zones may be defined within the power system 1800. As used herein, a bus differential protection zone (or protection zone) may refer to an area of protection formed by one or more

buses. Merging two or more buses may result in a single protection zone that includes the merged buses. The protection zone of an unmerged bus may include only the bus itself. Examples of systems and methods for determining a current topology (*e.g.*, merging buses and the like) are provided above in conjunction with Figure 7A, 8A, 9, and 10. Other examples of systems for determining bus differential protection zones are provided in United States Patent No. 6,411,865 to Qin et al., which is entitled "System for Protection Zone Selection in Microprocessor-Based Relays in an Electric Power system," and is hereby incorporated by reference in its entirety.

[00236] The power system 1800 includes three switches: switch 1834 is configured to selectively connect buses 1850 and 1860; switch 1836 is configured to selectively connect buses 1850 and 1870; and switch 1838 is configured to selectively connect buses 1860 and 1880. Closing a switch 1834, 1836, and/or 1838 may cause two or more of the buses 1850, 1860, 1870, and/or 1880 to merge into a protection zone with multiple buses (*e.g.*, the buses may merge into a "single" bus differential protection zone for the purposes of the differential current protection scheme). For example, closure of the switch 1834 while the switches 1836 and 1838 are open causes buses 1850 and 1860 to merge into a protection zone that includes buses 1850 and 1860, while the buses 1870 and 1880 remain in separate respective protection zones. Accordingly, in this configuration (wherein switch 1834 is closed and switches 1836 and 1838 are open), the power system 1800 would include three protection zones: a first protection zone comprising the buses 1850 and 1860, a second protection zone comprising the bus 1870, and a third protection zone comprising the bus 1880. Bus differential protection may be provided within each of the three protection zones.

[00237] The power system 1800 includes circuit breakers 1802, 1804, 1806, 1808, 1810, 1812, 1814, and 1816 (the Figure 18 circuit breakers). The Figure 18 circuit breakers may be electrically coupled to respective conductors 1801, 1803, 1805, 1807, 1809, 1811, 1813, and 1815 to selectively interrupt power flow thereon. Although Figure 18 is a single line diagram, each of the conductors 1801, 1803, 1805, 1807, 1809, 1811, 1813, and/or 1815 could include multiple lines (*e.g.*, a conductor line for each phase of a three-phase system)

[00238] The Figure 18 circuit breakers may be communicatively coupled to respective IEDs (*e.g.*, IEDs 1840, 1842, 1844, 1846, and/or 1848). The Figure 18 IEDs may be configured to monitor conditions on the conductors 1801, 1803, 1805, 1807, 1809, 1811, 1813, and/or 1815. In the event of a fault occurring within the power system

1800, the Figure 18 IEDs may be configured to cause one or more of the Figure 18 breakers to trip to isolate the fault. As will be discussed below, the data processor 1890 may direct the operation of multiple Figure 18 IEDs to isolate bus faults spanning multiple buses and/or IEDs.

- 5 **[00239]** The Figure 18 IEDs may receive current measurements from one or more measurement devices located at various locations within the power system 1800: the IED 1840 receives current information from the CT 1818; the IED 1842 receives current information from CTs 1822, 1824, and 1826; the IED 1844 receives current information from CTs 1830 and 1832; the IED 1846 receives current information from the CT 1828; 10 and the IED 1848 receives current information from CT 1820. In addition, the Figure 18 IEDs may obtain dynamic topology information, such as the status of the Figure 18 circuit breakers, the status of the Figure 18 switches (*e.g.*, switches 1834, 1836, 1838), the status of other switch components (not shown) in the power system 1800, and/or the real-time status and/or state of other components (terminals, transformers, 15 switchgear, etc.). The Figure 18 IEDs may comprise phasor measurement units (PMUs) (or may incorporate and/or be communicatively coupled to a PMU) capable of calculating synchronized phasors, time-stamped phasors, and/or synchrophasors. In some embodiments, the Figure 18 IEDs may transmit the current information received from the CTs as synchrophasors (*e.g.*, according to IEEE C37.118).
- 20 **[00240]** The Figure 18 IEDs may transmit the measurement data (*e.g.*, comprising time-stamped current and/or dynamic topology data) to a data processor 1890, which, as described above in conjunction with Figure 4, may comprise a time alignment module 1892 and a real-time system 1894. The time alignment module 1892 may time-align the time-stamped data received from the Figure 18 IEDs as described above.
- 25 **[00241]** The run-time system 1894 may provide for fast and accurate protection of the power system 1800. Accordingly, the run-time system 1894 may be configured to process the dynamic topology data received from the Figure 18 IEDs to determine a current topology of the power system 1800, which may include one or more bus differential protection zones. The current topology and/or protection zone information 30 may be used to detect busbar faults within the power system 1800 using the time-stamped current measurements received from the Figure 18 IEDs. Responsive to detecting a fault within a bus differential protection zone, the data processor 1890 may transmit one or more protective control signals (*e.g.*, circuit breaker trip signals) to one or more of the Figure 18 IEDs to clear the fault.

[00242] The run-time system 1894 may include a state and topology processor (STP) 1896, which may be configured to dynamically determine one or more protection zones within the power system 1800 in real-time. As discussed above, a bus differential protection zone (protection zone) may comprise one or more buses; buses that are electrically connected (by one or more of the switches 1834, 1836, and/or 1838 or other component) may be merged into a single protection zone, and unmerged buses may be included in their own, separate protection zones.

[00243] For example, if the switch 1836 is closed, the buses 1850 and 1870 may be included in the same protection zone, which may include the IEDs 1848 and 1842. The STP 1896 may manage the monitoring and/or protection of the protection zone across the IEDs 1848 and 1842, which may provide for faster and more accurate protection of the protection zone that would be possible by either of the IEDs 1848 and/or 1842 separately. The STP 1896 may use current and/or dynamic topology information received from both of the IEDs 1848 and 1842 to monitor the protection zone for faults and/or direct protective actions taken thereby.

[00244] In an alternative embodiment, the data processor 1890 and/or the STP 1896 may comprise and/or be implemented within an IED capable of receiving electric power information from various conductors (*e.g.*, via respective current transformers), calculating synchrophasors therefrom, operating circuit breakers, and/or coordinating the operation of other IEDs in a real-time basis. For instance, the data processor 1890 and/or the STP 1896 could be implemented within and/or in conjunction with one or more of the Figure 18 IEDs.

[00245] The STP 1896 may be configured to provide the monitoring and/or protective functions described above in conjunction with the STP 560 of Figure 5. Alternatively or in addition, the STP 1896 may be configured to provide distributed bus differential protection. One example of an STP 1896 configured to provide distributed bus differential protection is described below in conjunction with Figure 19.

[00246] Figure 19 is a block diagram 1900 of one embodiment of a STP 1996 configured to provide distributed differential bus protection. The STP 1996 of Figure 19 may include a topology processor 1970, a current processor 1980 and/or a voltage processor 590, which may operate similarly to the modules 570, 580 and 590 described above in conjunction with the STP 560 of Figure 5. In some embodiments, the voltage processor 590 (along with the voltage topology 592 data, voltage measurement data 594, and corresponding outputs 595) may be omitted.

[00247] The topology processor 1970 may receive dynamic topology data (*e.g.*, switch status, breaker status, etc.) and may output a current topology 1982 and/or corrected current measurements (not shown) as described above (*e.g.*, as described in connection with the topology processor 570 of Figure 5 and/or Figure 7A, 8A, and/or 10). In addition, the topology processor 1970 may be configured to dynamically determine one or more bus differential protection zones based on the topology data (*e.g.*, according to electrical connection(s) between one or more buses). In some embodiments, a bus differential protection zone may be defined as a list of current branches within the protection zone (*e.g.*, the current branches that are electrically connected to the busbars within the protection zone). The bus differential protection zones may be included in the current topology 1982 and/or may be provided as a separate output 1982.1 of the topology processor 1970.

[00248] As discussed above, the current processor 1980 may be configured to output refined current measurements 585.1. In some embodiments, the refined current measurements 585.1 may flow to the current differential element 1906 for use in the distributed bus differential protection scheme. Alternatively, the current differential element 1906 may use raw and/or corrected current measurements provided by the topology processor 1970.

[00249] The protection zone information 1982.1 and the refined current measurements 585.1 may flow to a current differential element 1906, which may be configured to implement a bus differential protection scheme for each of the protection zones. As shown in Figure 19, the current differential element 1906 may be implemented within the STP 1996 and/or as a separate component (*e.g.*, outside of the STP 1996). In some embodiments, the current differential element may be included as a component of and/or within the current processor 1980.

[00250] The current differential element 1906 may use the protection zone information 1982.1 and the refined, time-aligned current measurements 585.1 to detect faults using a current differential element and/or based upon the evaluation of a current differential operating condition. The STP 1996 and/or the current differential element 1906 may be capable of concurrently providing protection to any number of protection zones. Accordingly, the STP 1996 and/or the current differential element 1906 may incorporate multiple current differential elements (such as 1906) capable of operating in parallel. Alternatively, or in addition, the STP 1996 and/or current differential element 1906 may be capable of implementing bus differential protection for a large number of

protection zones in serial (*e.g.*, the STP 1996 and/or current differential element 1906 may operate at a higher clock frequency than the sample frequency of the current measurements 584, which may allow plural protection zones to be protected during each measurement period). Accordingly, the STP 1996 should not be considered to be limited as to the number of current differential element(s) 1906 provided therein and/or to the number of bus differential protection zones that may be concurrently protected.

[00251] Responsive to detecting a bus fault within one or more of the protection zones, the STP 1996 and/or the current differential element 1906 may be configured to generate one or more protective control signals 1924. The protective control signals 1924 may be configured to isolate or clear the fault, inform other devices of the fault (*e.g.*, other protective devices or IEDs), or the like. Alternatively, or in addition, the protective control signals 1924 include one or more alarm signals for display to a user via a HMI (not shown). The protective control signals 1924 may include circuit breaker trip commands configured to trip breakers on the conductors that are supplying current to the fault. The protective control signals 1924 may be issued to the one or more IEDs to which the circuit breakers are coupled. Alternatively, or in addition, the protective control signals 1924 may be issued directly to the one or more of the circuit breakers. The protective control signals may be adapted according to the current topology information 1982. For example, the current topology information 1982 may indicate which branches are supplying current to the faulted protection zone. The protective control signals 1924 may be adapted according to the protective and/or control components available in the electrical power system.

[00252] For each of the protection zones, the current differential element 1906 may evaluate a current differential operating condition. Evaluating the operating condition may comprise calculating a restraining current I_{RT} and an operating current I_{OP} . The current differential element 1906 may operate (*e.g.*, detect a fault within the protection zone) if the operating condition of the element 1906 is satisfied. The operating condition may be satisfied if the operating current I_{OP} is greater than the scaled restraining current I_{RT} (scaled by a slope characteristic) and a pickup current threshold I_{PU} :

$$I_{OP} > \max\{SLP \cdot I_{RT}, I_{PU}\} \quad \text{Eq. 2.0}$$

[00253] The restraining current I_{RT} and the operating current I_{OP} may be calculated in a number of different ways. Equations 2.1 and 2.2 below provide one example;

however, any means for calculating the restraining current I_{RT} and the operating current I_{OP} could be used under the teachings of this disclosure:

$$I_{RT} = |I_{01}| + |I_{02}| + |I_{03}| + |I_{04}| \dots + |I_n| \quad \text{Eq. 2.1}$$

$$I_{OP} = |I_{01} + I_{02} + I_{03} + I_{04} \dots + I_n| \quad \text{Eq. 2.2}$$

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[00254] In Equations 2.1 and 2.2, the current values I_{01} through I_n may be measurements of the currents flowing into a protection zone (e.g., on the branches within the protection zone). The measurements may be corrected for polarity and other factors (e.g., current transformer characteristics) according to the current topology information 1982 as described above. Alternatively, or in addition, the measurements may be refined current measurements 585.1 generated by the current processor 1980.

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[00255] The restraining current I_{RT} may be scaled by a slope characteristic SLP , which may be defined on a per-protection zone and/or per-bus basis (e.g., defined in the static and/or dynamic current topology information 1982). The value of the slope characteristic SLP may determine the sensitivity of the differential element. Some embodiments may employ a dual slope and/or adaptive slope characteristic, which may be used to change the sensitivity of the element responsive to conditions in the power system (e.g., an external fault or the like). Examples of various slope characteristics are described in United States Patent No. 6,356,421 to Armando Guzman-Casillas et al., and entitled, "System for Power Transformer Differential Protection" which is hereby incorporated by reference in its entirety. The current differential element 1906 may include a harmonic blocking module and/or be harmonically restrained. The harmonic blocking and harmonic restraint elements may operate in parallel. Examples of current differential elements incorporating harmonic blocking and harmonic restraint in parallel are described in United States Patent Application No. 12/424,705 filed April 16, 2009, and entitled, "Differential Element with Harmonic Blocking and Harmonic Restraint Operating in Parallel," which is hereby incorporated by reference in its entirety.

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[00256] Responsive to detecting a busbar fault within a particular protection zone (e.g., detecting that the operating current I_{OP} is greater than both the scaled restraining current I_{RT} and the pickup current threshold I_{PU}), one or more protective control signals 1924 may be issued. As discussed above, the protective control signals 1924 may be adapted to isolate the busbar fault and, as such, may be configured to trip circuit breakers coupled to the one or more conductors supplying current to the fault. The circuit breakers may be selected according to the current topology information 1982

and/or protection zone information 1982.1. In some embodiments, the protective control signals 1924 may be transmitted to one or more IEDs communicatively coupled to the respective circuit breakers (not shown). As discussed above, a protection zone may include plural IEDs. Accordingly, the STP 1996 may direct the operation of multiple IEDs by receiving topology and current information from the IEDs and directing the protective actions taken by the IEDs (according to the current topology information 1982).

[00257] Figure 20 is a functional block diagram of one embodiment of a current differential element, such as the current differential element 1906 of Figure 19. The differential element 2006 may receive an operating current I_{OP} input 2010 and a restraining current I_{RT} input 2012. As discussed above, the I_{OP} input 2010 may be calculated according to Equation 2.2 and the I_{RT} input 2012 may be calculated according to Equation 2.1. In other embodiments, an alternative technique for calculating the operating current I_{OP} and/or the restraining current I_{RT} may be used.

[00258] The inputs 2010 and 2012 flow to the differential element characteristic 2002, which may scale the restraining current I_{RT} by one of the slope characteristics $SLP1$ 2026 or $SLP2$ 2028. The selection of the slope characteristic 2026 or 2028 may be based upon an operating mode of the current differential element 2006. The differential element 2006 may be configured to operate in a normal mode and a high-security mode. The operating mode may be determined by an external fault signal 2003 produced by an external fault detection logic module 2004. When an external fault is detected by the module 2004 (and the external fault signal 2003 is asserted), the current differential element 2006 may be configured to operate in the high-security mode. Accordingly, the differential characteristic 2002 may scale the restraining current I_{RT} input 2012 by the less-sensitive, high-security slope constant $SLP2$ 2028; otherwise, the slope constant $SLP1$ 2026 may be used. One embodiment of an external fault detection logic module 2004 is described below in conjunction with Figure 21.

[00259] The characteristic 2002 asserts an FDIF output 2018 if the operating current I_{OP} input 2010 is greater than the scaled restraining current. An output 87O 2016 is asserted if the operating current I_{OP} input 2010 is greater than the pickup current threshold I_{PU} . The outputs 2016 and 2018 flow to an AND gate 2006, which asserts the signal P87R 2022 if the operating current I_{OP} input 2010 is greater than both the scaled restraining current and the pickup current threshold I_{PU} .

[00260] In some embodiments, the signal P87R 2022 may be used as a bus fault detection signal. In the Figure 20 embodiment, the P87R 2022 signal flows to an adaptive security timer 2008, which may assert a bus fault detection signal 87R 2024 if the P87R 2022 signal is maintained in an asserted state for a pre-determined time period and/or for a pre-determined number of measurements. If the P87R signal 2022 is asserted for the required time period, the bus fault detection signal 87R 2024 may be asserted. The adaptive security timer 2008 may be capable of operating in a normal mode and in a high-security mode in accordance with the external fault signal 2003. When the external fault signal 2003 is asserted, the adaptive security timer 2008 may operate in the high-security mode. Operation in the high-security mode may cause the adaptive security timer 2008 to increase the pre-determined time period (or pre-determined number of measurements).

[00261] The 87R 2024 output may indicate detection of a bus fault within a particular protection zone. The signal 2024 may be used to generate one or more protective control signals (*e.g.*, signals 1924 of Figure 19). Accordingly, the signal 2024 may flow to a local PMCU (such as the local PMCU 480 described in conjunction with Figure 4) or another protective device. The bus fault detection signal 2024 may cause one or more protective control signals to be issued, which, in turn, may cause one or more protective actions to take place. For example, one or more of the protective control signals (not shown) may be issued to IEDs coupled to the circuit breakers that control the conductors that are supplying current to the fault. As discussed above, in certain bus arrangements, a protective zone may include multiple IEDs. Accordingly, the protective control signal(s) issued as a result of assertion of the 87R 2024 signal may be transmitted to multiple IEDs (in accordance with the configuration of the protective zone and/or the current topology information). Alternatively, or in addition, the current differential element 2006 and/or the STP 1996 of Figure 19 may be implemented within and/or in conjunction with a local IED and/or PMCU (not shown). In this case, the signal 2024 may cause the local device to trip the appropriate circuit breakers to clear the fault.

[00262] Figure 21 is a functional block diagram of one embodiment of an external fault detection logic module 2104, such as the module 2004 of Figure 20. The external fault detection logic module 2104 may detect an external fault condition based upon changes in the restraining current I_{RT} and the operating current I_{OP} with respect to time. For example, if there is a significant change in the restraining current I_{RT} and a small

(less than a pre-determined threshold) change in operating current I_{OP} , an external fault condition may be detected.

[00263] A comparator 2114 compares a restraining current change ΔI_{RT} input 2102 to a restraining current change threshold value $\Delta I_{RT_THRESHOLD}$ 2101. A DRT output 2128 of the comparator 2114 is asserted if the restraining current change ΔI_{RT} input 2102 is greater than the threshold 2101. A comparator 2116 compares an operating current change ΔI_{OP} input 2106 to an operating current change threshold value $\Delta I_{OP_THRESHOLD}$ 2105. A DOP output 2130 of the comparator 2116 is asserted if the operating current change ΔI_{OP} input 2106 is greater than the threshold 2105. The restraining current change ΔI_{RT} input 2102 and the operating current change ΔI_{OP} input 2106 may be generated by calculating respective time derivatives of the restraining current I_{RT} and the operating current I_{OP} (e.g., using a numerical technique). The derivatives may be discrete if the restraining current I_{RT} and/or the operating current I_{OP} are based on measurement samples (e.g., comprise discrete measurements made at a particular sampling rate) and/or may be continuous if the restraining current I_{RT} and/or the operating current I_{OP} are based on continuous current values.

[00264] The DRT signal 2128 flows to an input of an AND gate 2120, and the DOP signal 2130 flows to an inverted input of the AND gate 2120. Accordingly, the output 2121 of the AND gate 2120 may assert if the DRT signal 2128 is asserted and the DOP 2130 signal is deasserted (e.g., if the restraining current change ΔI_{RT} input 2102 is greater than the threshold 2101 and the operating current change ΔI_{OP} input 2106 is less than the threshold 2105). The output 2121 flows to the external fault condition block 2122, which may comprise a security timer or other device configured to assert the output 2123 if the input 2121 is asserted for a pre-determined time period and/or pre-determined number of measurements.

[00265] In some embodiments, the output 2123 of the external fault condition block 2122 may flow to a hold timer 2124. The hold timer 2124 may be configured to keep the external fault output 2103 asserted for a pre-determined time period and/or pre-determined number of cycles (e.g., 60 measurements) after the input 2123 is deasserted.

[00266] Figure 22 is a block diagram of one embodiment of a system 2200 for distributing time information to various IEDs, such as the Figure 18 IEDs discussed above. According to Figure 22, a master clock 2202 provides time information to various slave clocks 2204 and 2206. The slave clocks 2204 and 2206 may be time-

coordinated with the master clock 2202. The slave clocks 2204 and 2206 may be configured to provide a common time (originating from the master clock 2202) to the IEDs 2208 and 2210 (although only two IEDs 2208 and 2210 are depicted, the system 2200 could include any number of IEDs). Thus, the IEDs 2208 and 2210 may operate on a common time (*e.g.*, may be synchronized). As such, timestamp information applied by the IEDs 2208 and 2210 (*e.g.*, to measurement data obtained thereby) may be capable of being time-aligned to one another. The master clock 2202 may be any clock or clock signal available to the slave clocks 2204 and 2206. As such, the master clock 2202 may provide a common time to the slave clocks 2204 and 2206 (*e.g.*, act as an absolute time or time reference to the slave clocks 2204 and 2206). For example, the master clock 2202 may be implemented as an IRIG time signal from a GPS system, a WWB signal, a WWVB signal, an atomic clock, or any other time source. The slave clocks 2204 and 2206 may be clocks available within a particular building, substation, or the like. Further, the slave clocks may be within the IEDs 2208 and/or 2210. The IEDs 2208 and 2210 may apply timestamp information to data collected from a power system (not shown). As discussed above, the measurement information may include phase current measurements, phase voltage measurements, topology measurements, and the like. The timestamp information may be supplied by the respective slave clocks sources 2204 and/or 2206 communicatively coupled to the IEDs 2208 and 2210. The time-stamped data may be communicated to a data processor 2290 via a network, such as a WAN or a LAN 2212. This arrangement may facilitate a distributed differential protection scheme and zone selection of a distributed bus arrangement, such as that shown in the power system 1800 of Figure 18. Further, the time synchronization between the IEDs 2208 and 2210 may allow for consistent timestamp information to be applied thereby. As discussed above, the data processor 2290 and/or STP implemented therein (not shown) may time-align the time-stamped data received from the IEDs 2208 and 2210 and may use the aligned data to provide one or more monitoring and/or protective functions, such as distributed bus differential protection.

[00267] Figure 23 is a block diagram 2300 of one embodiment of a data processor 2302 capable of sending commands to one or more IEDs (such as IEDs 2304, 2306, 2308). The data processor 2302 may include a plurality of communications channels for receiving power system data from a plurality of power system devices or elements (such as IEDs 2304, 2306, 2308) associated with an SEPSN. As discussed above, the

power system data may be communicated to the data processor 2302 according to any of a number of different protocols.

[00268] The data processor 2302 may include a time alignment module 2310 configured to correlate and time align incoming power system data (*e.g.*,

5 measurements, topology information, and the like). The time-aligned power system data is provided to the run-time system 2320. The run-time system 2320 may include one or more modules, including a power calculation (PWRC) module 2322, a phase angle difference monitor (PADM) 2324, a modal analysis (MA) module 2326, a substation state and topology processor (SSTP) 2328, and a command module 2314.

10 The run-time system 2320 may further include a user-programmable tasks module 2330 that may operate according to the IEC 61131-3 specification.

[00269] A bus differential protection scheme as described herein may be provided by the run-time system 2320. In some embodiments, the bus differential protection scheme may be provided by the user-programmable tasks module 2330. Responsive
15 to the bus differential protection scheme detecting a fault on a particular bus, the data processor 2320 and/or user-programmable tasks module 2330 may be configured to cause one or more protective actions to take place. For example, a command may be sent to a particular IED (2304, 2306, and/or 2308) to trip a breaker, trip one or more buses, assert one or more alarms, or the like.

20 **[00270]** In some embodiments, the data processor 2302 may issue commands using the command module 2314, which may be configured to communicate with the IEDs 2304, 2306, and/or 2308 according to various protocols and/or messaging formats. The data processor 2302 may transmit a message to the command module 2314, which may send a corresponding message to the recipient IED(s) 2304, 2306, and/or
25 2308 in a particular protocol and/or message format, such as fast operate, IEC 61850 GOOSE, Mirrored Bits® communication, or the like (Mirrored Bits® is a registered trademark of Schweitzer Engineering Laboratories, Inc. of Pullman, WA). Accordingly, the data processor 2302 may be capable of receiving measurements and other data from the SEPSN (from various IEDs or other devices), providing a bus differential
30 protection scheme, and sending commands to take one or more protective actions to one or more IEDs 2304, 2306, and/or 2308 distributed within the SEPSN based on the results of the bus differential protection scheme in a time-sensitive manner.

[00271] Figure 24 is a flow diagram of one embodiment of a method 2400 for providing distributed bus differential protection. At step 2410, the method may start and

be initialized, which may comprise loading one or more computer-readable instructions from a computer-readable storage medium, accessing one or more communications interfaces, accessing one or more measurement devices (*e.g.*, current transformers, IEDs, PMUs, or the like), and so on. The instructions comprising the method 2400 may be embodied as one or more discrete software modules on a computer-readable storage medium. Certain of the instructions and/or steps of the method 2400 may be implemented as hardware components, such as digital logic components, analog circuits, or the like. Moreover, one or more of the instructions may be adapted to interface with particular hardware components, such as communications interfaces, measurement devices, or the like. Therefore, one or more of the steps of the method 2400 may comprise and/or be tied to particular machine components.

[00272] At step 2420, time-stamped measurement data may be received from one or more IEDs. As discussed above, the time-stamped measurement data may be embodied as synchrophasor measurements according to IEEE C37.118. The measurements may be transmitted to the method 2400 over a network by one or more IEDs located within a power system (*e.g.*, the power system 1800 of Figure 18). The IEDs may be positioned at a significant distance from one another and/or the computing device implementing the method 2400 (*e.g.*, a state and topology processor or the like). The IEDs may be electrically and/or communicatively coupled to the electrical power system via one or more current transformers (or other devices) to obtain the measurement data therefrom.

[00273] Receiving the measurement data at step 2420 may comprise time-aligning the measurement data using the timestamp information associated therewith, accessing correction factors associated with the measurement data (according to a topology of the power system and/or properties of the measurement device(s) used to acquire the measurements), applying the correction factors to the data, and the like as described above (*e.g.*, in conjunction with Figure 10). In some embodiments, the current measurements may be refined as described above.

[00274] The measurement data may comprise time-stamped current measurements obtained at various branches within the electrical power system. The measurement data may further comprise dynamic topology data, such as the state of one or more switches, circuit breakers, branches, and the like.

[00275] At step 2430, a current topology may be determined. As described above (*e.g.*, in conjunction with Figures 7A, 8A, 9, and 10), the current topology may be

determined using the dynamic topology data received at step 2420, as well as static topology data associated with the electrical power system. The static topology data may be stored in a computer-readable storage medium and may describe the topology of the electrical power system. The dynamic topology data (received at step 2420) may indicate the state of various components of the power system (*e.g.*, the state of circuit breakers, switches, and other components within the power system that may determine a dynamic topology of the bus arrangement). The combination of the static and the dynamic topology data may allow for a real-time topology and/or state of the power system to be determined.

[00276] At step 2440, the current topology may be used to identify one or more bus differential protection zones. As described above, a protection zone may include one or more buses. Buses that are merged (as indicated by the dynamic topology information received at step 2420) may be included in the same protection zone. In some embodiments, a protection zone may comprise and/or be defined by a list of current branches within the protection zone. Although determining the protection zones is shown as a separate step in Figure 24, in some embodiments, the protection zones may be determined concurrently with the current topology at step 2430.

[00277] At step 2450, the method 2400 may iterate over each of the protection zones identified at step 2440. The iteration may allow the method 2400 to implement a current differential protection function within each protection zone. Although this is depicted in Figure 24 as a serial iteration over each of the protection zones, in other embodiments, the method 2400 could perform current differential protection for multiple protection zones in parallel (*e.g.*, using multiple current differential elements operating in parallel).

[00278] At step 2460, the method may implement a current differential protection function for a particular protection zone. As discussed above, this may comprise evaluating a current differential operating condition for the protection zone, which may comprise calculating a restraining current I_{RT} and an operating current I_{OP} for the protection zone (*e.g.*, according to the current topology determined at step 2430 and the protection zone determination of step 2440). In some embodiments, the protection zone may be defined as a set of branches within the protection zone (*e.g.*, that supply current to/from the busbars in the protection zone). Accordingly, at step 2460, Equations 2.1 and 2.2 may be applied to the current measurements (received and processed at step 2420) corresponding to the branches of the protection zone identified

at step 2440 to calculate the restraining current I_{RT} and the operating current I_{OP} . The operating condition may be evaluated by comparing the operating current I_{OP} to the scaled restraining current I_{RT} and a pickup current threshold I_{PU} .

[00279] In some embodiments, the current differential protection of step 2460 may

5 comprise selecting an operating mode, which may comprise selecting one of a plurality of slope characteristics and/or time thresholds. For example, the current differential element 1996 discussed above in conjunction with Figure 19 may be capable of operating in a plurality of different operational modes, which may include an operational mode for normal operation, and a less-sensitive, high-security operational mode used
10 under certain circumstances (e.g., upon detection of an external fault). Therefore, step 2460 may comprise detecting an external fault (e.g., based upon the rate of change of the restraining and operating currents I_{RT} and I_{OP} as described above in conjunction with Figure 21). For instance, at step 2460, an external fault may be detected (and a high-security operational mode may be selected) if a change in the restraining current
15 I_{RT} exceeds a restraining current change threshold and a change in the operating current I_{OP} does not exceed an operating current change threshold for a pre-determined time period and/or a pre-determined number of measurements.

[00280] As discussed above, the current differential protection step 2460 may comprise scaling the restraining current I_{RT} by a slope characteristic, which may be
20 selected according to the operational mode determined above. For example, if an external fault is not detected, a first slope characteristic may be used, and, if an external fault is detected, a second, less-sensitive, high-security slope characteristic may be used.

[00281] At step 2462, a current differential operating condition of the particular bus
25 differential protection zone may be evaluated. The current differential operating condition may be evaluated by comparing the operating current I_{OP} to the scaled restraining current I_{RT} and a pickup current threshold I_{PU} . If the operating condition is satisfied (e.g., if the operating current I_{OP} is greater than both values) a bus fault may be detected and the flow may continue at step 2470; otherwise, the flow may continue
30 to step 2480.

[00282] In some embodiments, the detection of a bus fault may be supervised by a security timer. Accordingly, step 2462 may include the evaluation of the security timer. The security timer may indicate the time and/or the number of measurements that the operating condition has been satisfied (e.g., the time that the operating current I_{OP} has

been greater than the scaled restraining current I_{RT} and the pickup current threshold I_{PU}). The security timer may be compared to a pre-determined time threshold, which may specify the time and/or number of measurements that the operating condition must be maintained before a bus fault is detected. As discussed above, the time threshold
5 may be adaptable according to conditions detected within the power system. For example, a first time threshold may be used under normal conditions, and a second, high-security time threshold may be used if an external fault is detected. Although step 2462 is described as including a security timer evaluation step, in other embodiments, the security timer may be omitted (*e.g.*, a bus fault may be detected as soon as the
10 operating current exceeds the restraining current I_{RT} and the pickup current threshold I_{PU}).

[00283] If at step 2462 it is determined that the operating condition and/or security timer have been satisfied, the flow may continue at step 2470; otherwise, the flow may continue at step 2480.

[00284] At step 2470, a bus fault signal for the particular protection zone may be asserted. As discussed above, assertion of the bus fault signal may include generating and/or transmitting one or more protective control signals to one or more IEDs or other protective devices. The protective control signals may be adapted according to the current topology determined at steps 2430 and 2440 and/or the protective components
20 available in the power system (*e.g.*, circuit breakers, switches, etc.). The protective control signals may be transmitted to the IEDs via a network using a communications interface. Alternatively, or in addition, if the method 2400 includes a local IED and/or PMCU, the protective control signals may be used to directly configure one or more protective devices.

[00285] At step 2480, the method 2400 may determine whether additional protection zones remain to be processed. If so, the flow may continue to step 2450 where the next protection zone may be processed; otherwise, the flow may terminate at step 2490.

[00286] The above description provides numerous specific details for a thorough
30 understanding of the embodiments described herein. However, those of skill in the art will recognize that one or more of the specific details may be omitted, or other methods, components, or materials may be used. In some cases, operations are not shown or described in detail.

[00287] Furthermore, the described features, operations, or characteristics may be combined in any suitable manner in one or more embodiments. It will also be readily understood that the order of the steps or actions of the methods described in connection with the embodiments disclosed may be changed as would be apparent to those skilled in the art. Thus, any order in the drawings or Detailed Description is for illustrative purposes only and is not meant to imply a required order, unless specified to require an order.

[00288] Embodiments may include various steps, which may be embodied in machine-executable instructions to be executed by a general-purpose or special-purpose computer (or other electronic device). Alternatively, the steps may be performed by hardware components that include specific logic for performing the steps, or by a combination of hardware, software, and/or firmware.

[00289] Embodiments may also be provided as a computer program product including a computer-readable medium having stored instructions thereon that may be used to program a computer (or other electronic device) to perform processes described herein. The computer-readable medium may include, but is not limited to: hard drives, floppy diskettes, optical disks, CD-ROMs, DVD-ROMs, ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, solid-state memory devices, or other types of media/machine-readable medium suitable for storing electronic instructions.

[00290] As used herein, a software module or component may include any type of computer instruction or computer executable code located within a memory device and/or computer-readable storage medium. A software module may, for instance, comprise one or more physical or logical blocks of computer instructions, which may be organized as a routine, program, object, component, data structure, etc., that perform one or more tasks or implements particular abstract data types.

[00291] In certain embodiments, a particular software module may comprise disparate instructions stored in different locations of a memory device, which together implement the described functionality of the module. Indeed, a module may comprise a single instruction or many instructions, and may be distributed over several different code segments, among different programs, and across several memory devices. Some embodiments may be practiced in a distributed computing environment where tasks are performed by a remote processing device linked through a communications network. In a distributed computing environment, software modules may be located in local and/or remote memory storage devices. In addition, data being tied or rendered together in a

database record may be resident in the same memory device, or across several memory devices, and may be linked together in fields of a record in a database across a network.

5 **[00292]** It will be understood by those having skill in the art that many changes may be made to the details of the above-described embodiments without departing from the underlying principles of the disclosure.

[00293] What is claimed is:

1. A device for providing distributed bus differential protection to an electrical power system, comprising:

a communication module communicatively coupled to a plurality of intelligent electronic devices (IEDs) to receive current and dynamic topology measurements therefrom;

a topology processor communicatively coupled to the communication module and configured to determine a current topology of the electrical power system using the dynamic topology measurements, wherein the current topology comprises one or more bus differential protection zones; and

a current differential element communicatively coupled to the communication module and the topology processor and configured to provide differential protection for each of the one or more bus differential protection zones using the current measurements and the current topology.

2. The device of claim 1, wherein the measurements received from the IEDs comprise respective timestamps, the device further comprising a time alignment module configured to time align the measurements received from the IEDs using the measurement timestamps.

3. The device of claim 2, wherein the measurements received from the IEDs comprise synchrophasor current measurements.

4. The device of claim 2, wherein the IEDs are synchronized to a common time source.

5. The device of claim 1, further comprising a current processor communicatively coupled to the communication module and the topology processor, wherein the current processor is configured to apply one or more correction factors to the current measurements based upon the current topology to thereby calculate corrected current measurements, and wherein the differential element uses the corrected current measurements to provide differential protection for each of the one or more bus differential protection zones.

6. The device of claim 5, wherein the current processor is configured to produce refined current measurements based upon the corrected current measurements, and wherein the current differential element uses the refined current measurements to provide differential protection for each of the one or more bus differential protection zones.

7. The device of claim 1, wherein the current differential element is configured to provide differential protection of a particular bus differential protection zone by:

- calculating an operating current and a restraining current using the current measurements and the current topology;
- scaling the restraining current by a scaling characteristic to produce a scaled restraining current; and
- asserting a bus fault detection signal for the particular bus differential protection zone when the operating current exceeds the scaled restraining current and a pickup current threshold.

8. The device of claim 7, wherein the communication module is configured to transmit one or more protective control signals to one or more of the plurality of IEDs responsive to the assertion of the bus fault detection signal for the particular bus differential protection zone, and wherein the one or more protective control signals are generated using the current topology.

9. The device of claim 7, further comprising an external fault detection module communicatively coupled to the current differential element, wherein the current differential element is configured to select one of a plurality of scaling characteristics based on an external fault condition detected by the external fault detection module.

10. The device of claim 9, wherein the external fault detection module is configured to detect an external fault based on a change in the restraining current and a change in the operating current.

5

11. The device of claim 9, wherein the external fault detection module is configured to detect an external fault when a change in the restraining current exceeds a restraining current change threshold and a change in the operating current does not exceed an operating current change threshold.

10

12. The device of claim 9, wherein the differential element is configured to assert the bus fault detection signal for the particular protection zone when the operating current is greater than the scaled restraining current and the pickup current threshold for a selected time period, and wherein the differential element is configured to select the time period based on the external fault condition detected by the external fault detection module.

15

13. The device of claim 7, wherein the differential element is configured to assert the bus fault detection signal for the particular protection zone when the operating current is greater than the scaled restraining current and the pickup current threshold for one of a threshold time period and a threshold number of measurements.

20

14. The device of claim 1, wherein the dynamic topology measurements comprise one of a circuit breaker status and a switch status.

25

15. A method for providing distributed bus differential protection in an electrical power system, the method comprising:

receiving time-stamped current measurements and dynamic topology measurements from a plurality of intelligent electronic devices (IEDs) distributed within an electrical power system, wherein each of the plurality of IEDs is electrically coupled to respective portions of the power system to obtain measurement data therefrom;

30

time-aligning the current measurements to produce time-aligned current measurements;

determining a current topology of the electrical power system using the dynamic topology measurements, wherein the current topology comprises one or more bus differential protection zones (BDPZs);

5 providing differential protection for each BDPZ, wherein providing differential protection for a particular BDPZ comprises evaluating a current differential operating condition of the BDPZ using the current topology and the time-aligned current measurements and detecting a bus fault within the BDPZ when the operating condition is satisfied; and

10 transmitting a protective control signal to an IED responsive to detecting a bus fault within the particular BDPZ.

16. The method of claim 15, wherein evaluating the current differential operating condition for the particular BDPZ comprises:

calculating an operating current and a restraining current using the current topology and the time-aligned current measurements;

5 scaling the restraining current by a scaling factor to produce a scaled restraining current; and

comparing the operating current to the scaled restraining current and a pickup current threshold, wherein the current differential operating condition is satisfied when the operating current exceeds the scaled restraining current and the pickup current
10 threshold.

17. The method of claim 16, further comprising detecting an external fault in the electrical power system based upon a change in the operating current and a change in the restraining current.

15

18. The method of claim 17, wherein the restraining current is scaled by a first slope characteristic when an external fault is not detected, and is scaled by a second, high-security slope characteristic when an external fault is detected.

20 19. The method of claim 17, wherein the bus fault is detected within the BDPZ when the operating condition is satisfied for a selected time threshold, and wherein a first time threshold is selected when an external fault is not detected, and a second, high-security time threshold is selected when an external fault is detected.

25 20. The method of claim 15, wherein the bus fault is detected within the BDPZ when the operating condition is satisfied for one of a pre-determined time threshold and a pre-determined number of measurements.

30 21. The method of claim 15, wherein the time-stamped current measurements comprise synchrophasor current measurements.

22. The method of claim 15, wherein the IEDs are synchronized to a common time source.

23. A computer-readable storage medium comprising instructions to cause a computing device to perform a method, comprising:

receiving time-stamped measurement data from plural intelligent electronic devices (IEDs) distributed within an electrical power system, the time-stamped measurement data comprising time-stamped current measurements and dynamic topology measurements, wherein the IEDs are synchronized to a common time source;
time-aligning the time-stamped current measurements to produce time-aligned current measurements;

determining a current topology of the electrical power system using the dynamic topology measurements and a static topology of the electrical power system, wherein the current topology comprises one or more bus differential protection zones (BDPZs);

providing differential protection for each of the BDPZs, wherein providing differential protection for a particular BDPZ comprises,

calculating an operating current and a restraining current of the particular

BDPZ using the time-aligned current measurements and the current topology,

detecting an external fault state of the electrical power system,

scaling the restraining current by a selected one of a plurality of slope characteristics to produce a scaled restraining current, wherein the slope characteristic is selected according to the detected external fault state, and

detecting a bus fault when the operating current is greater than the scaled restraining current and a pickup current threshold for a selected time threshold, wherein the time threshold is selected according to the detected external fault state, and

transmitting one or more protective control signals to one or more of the IEDs responsive to detecting a bus fault in one or more of the BDPZs.

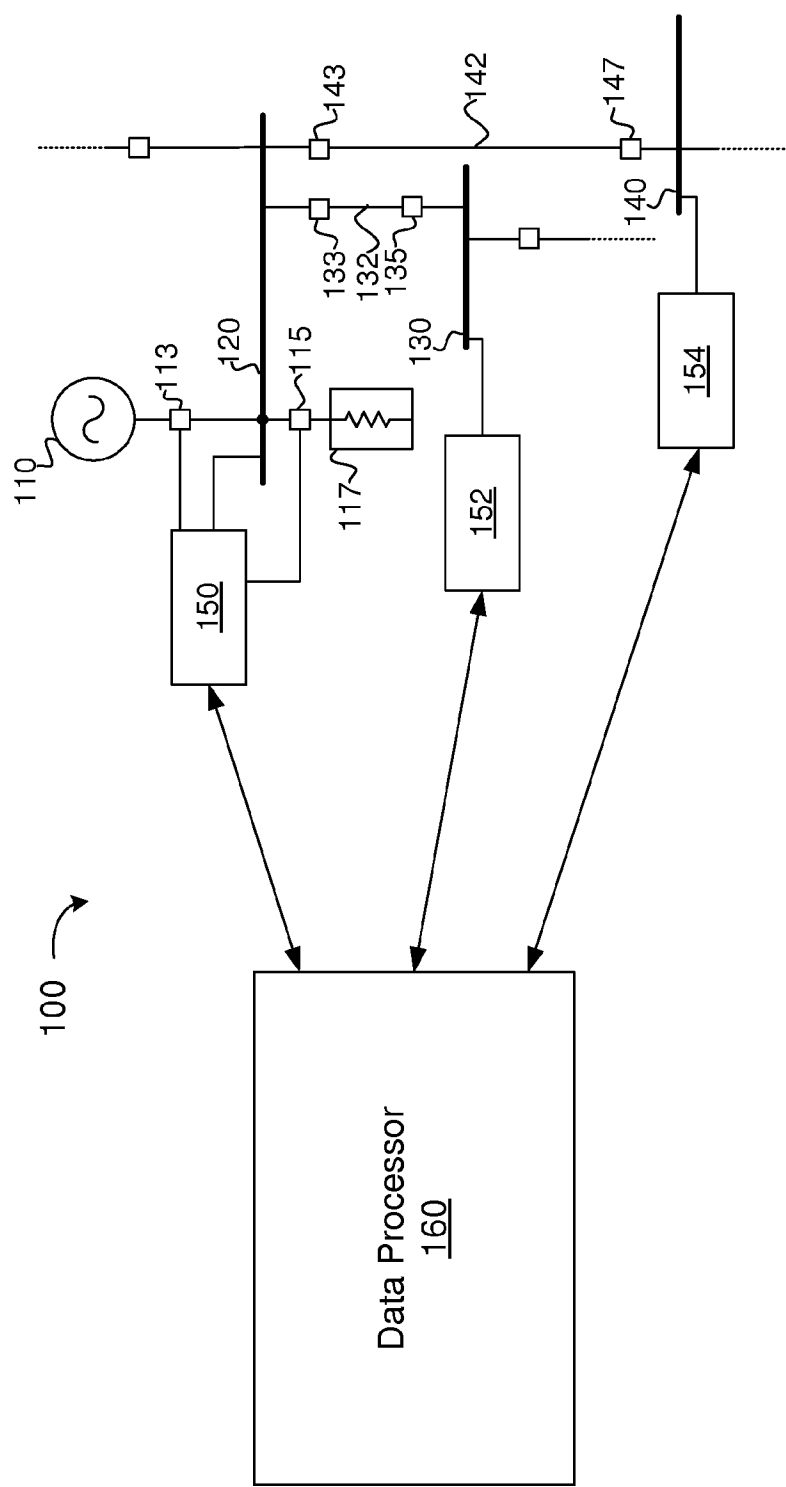


Figure 1

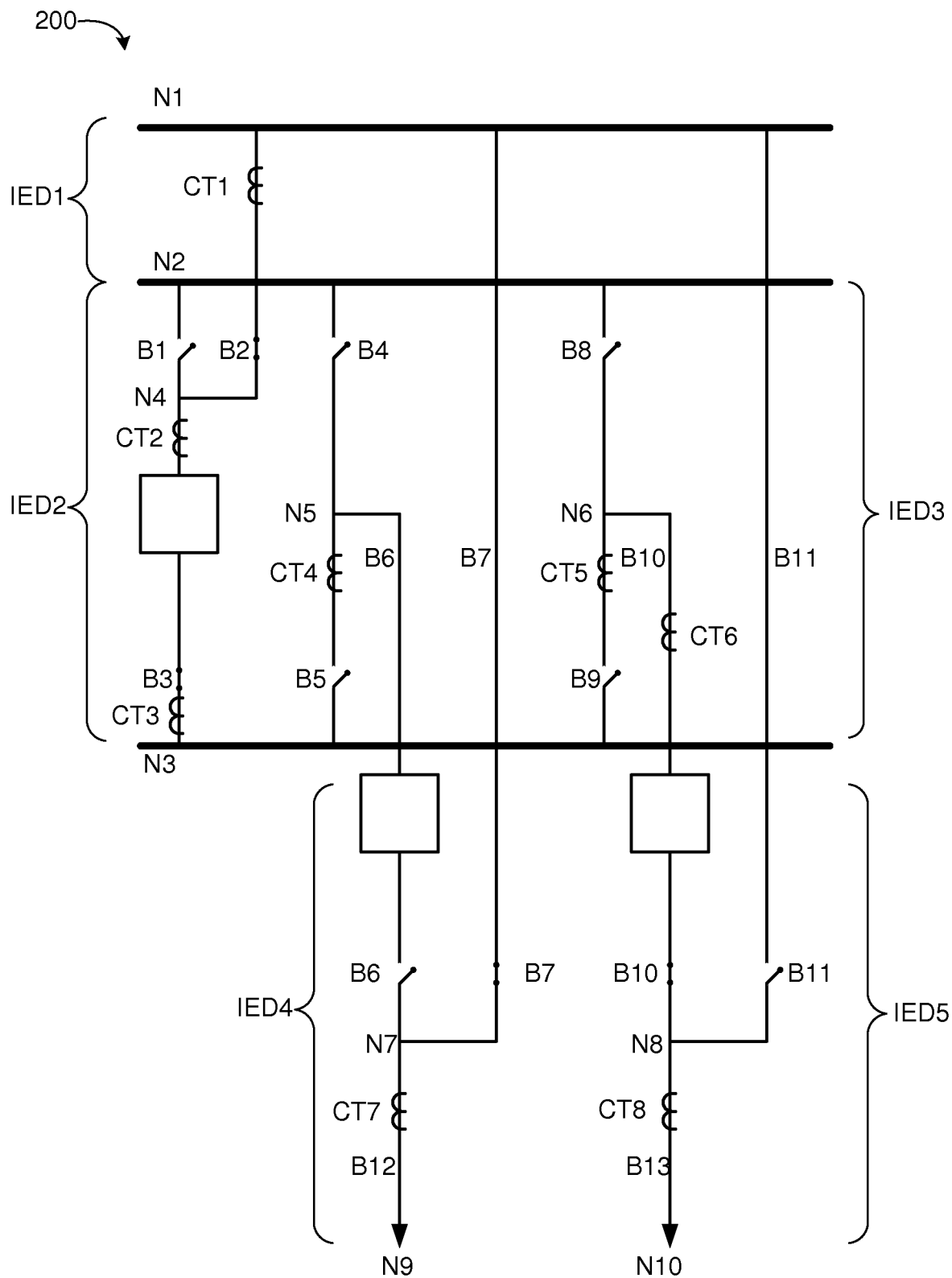


Figure 2A

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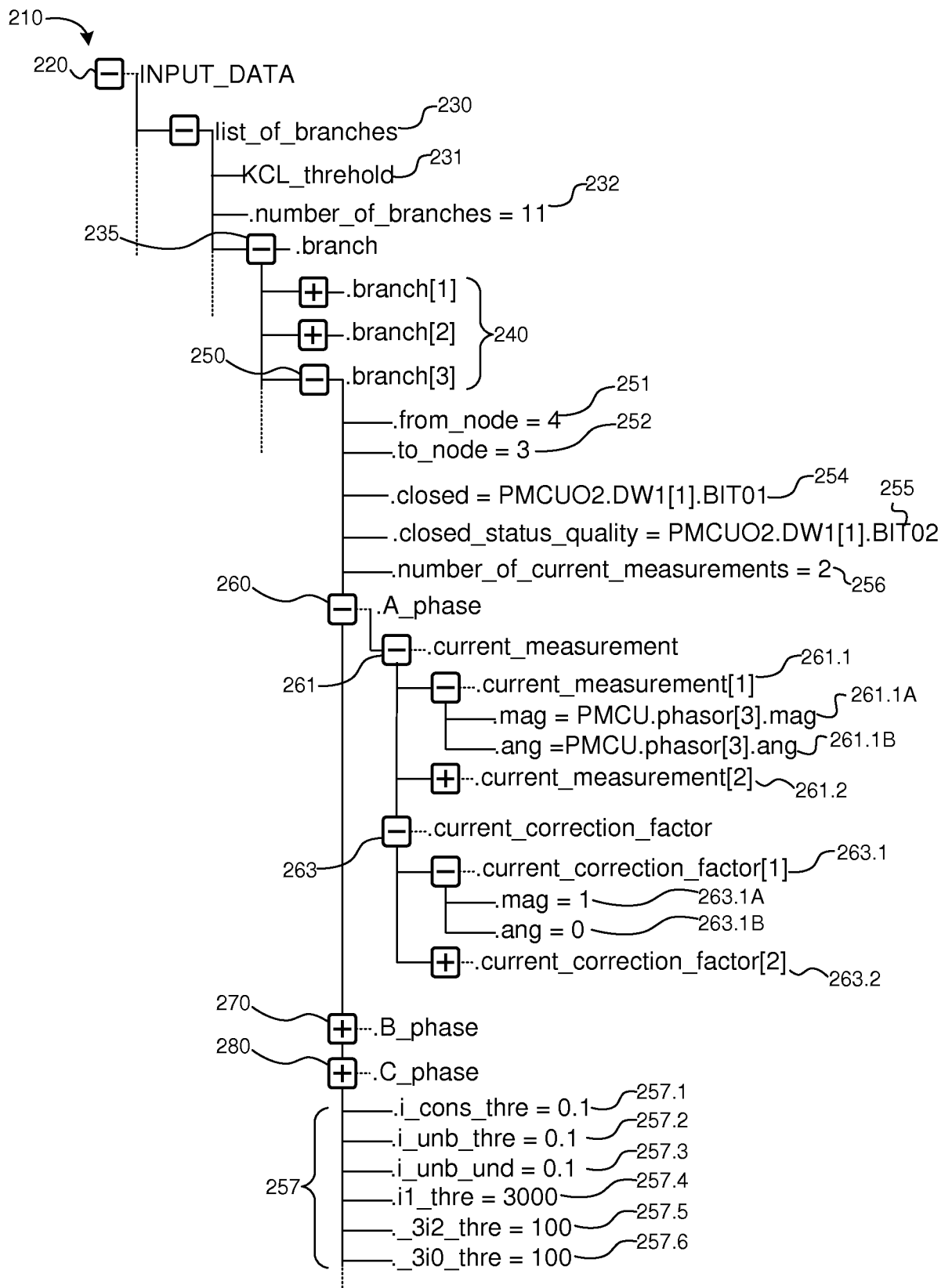


Figure 2B

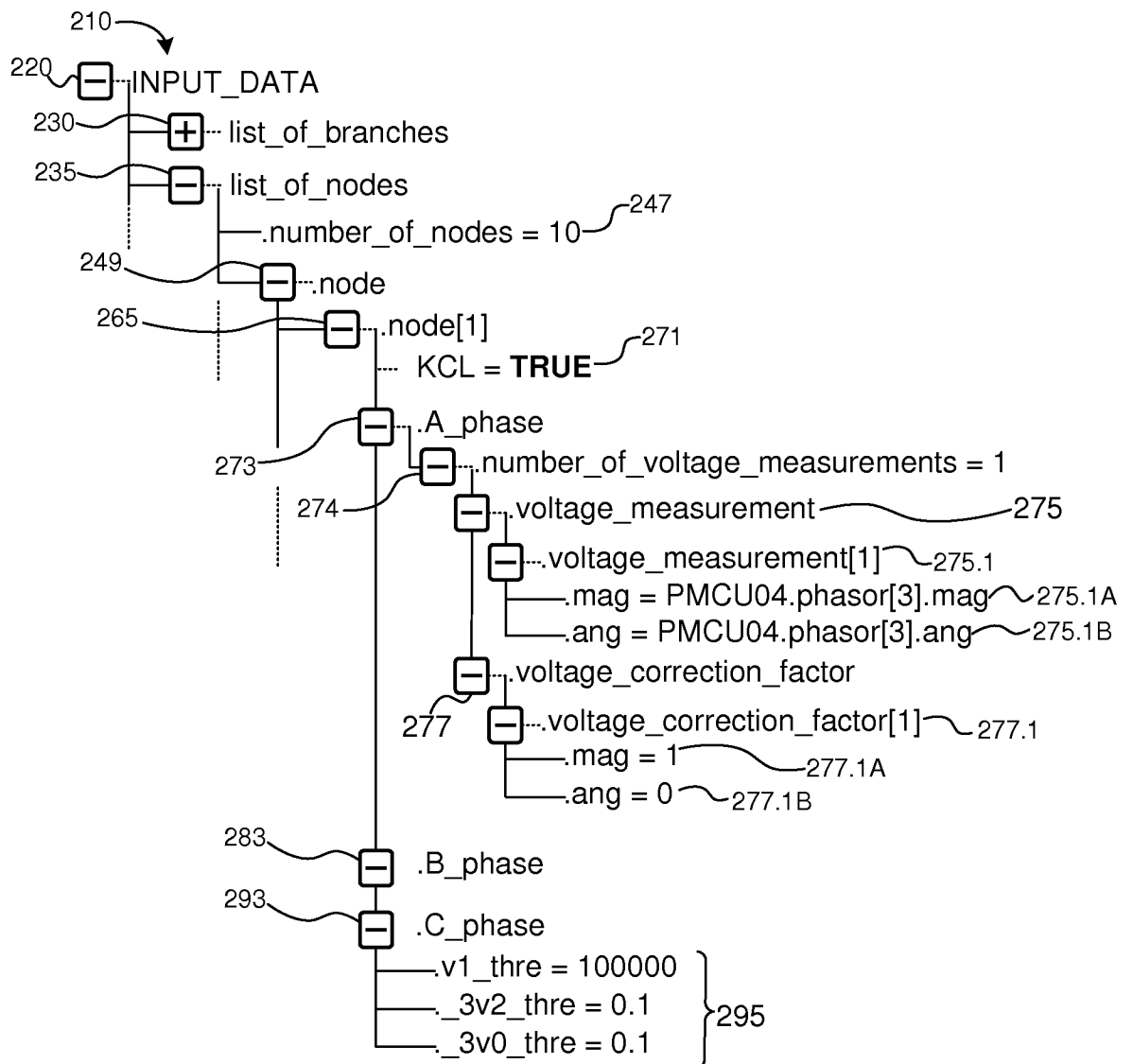


Figure 2C

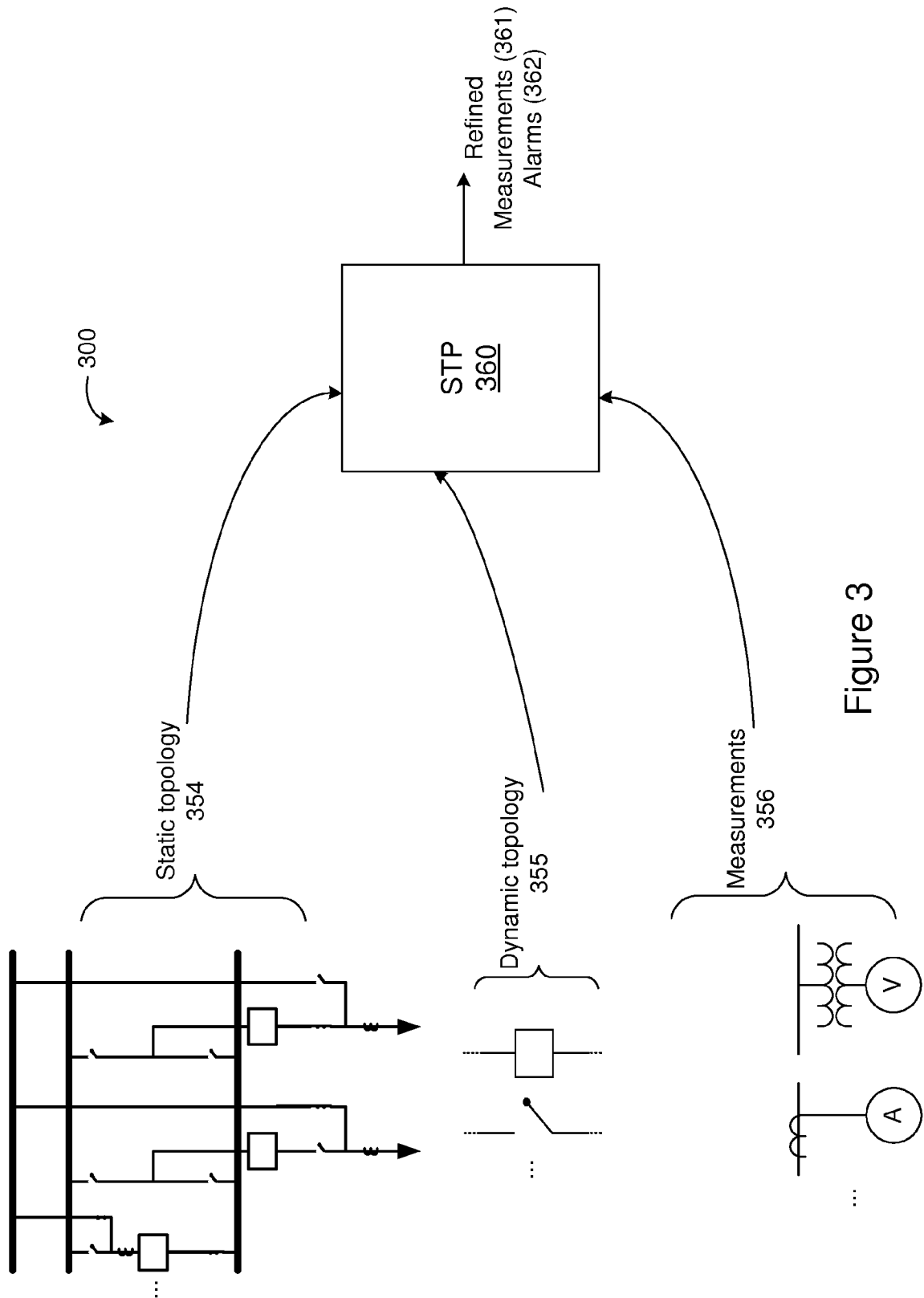


Figure 3

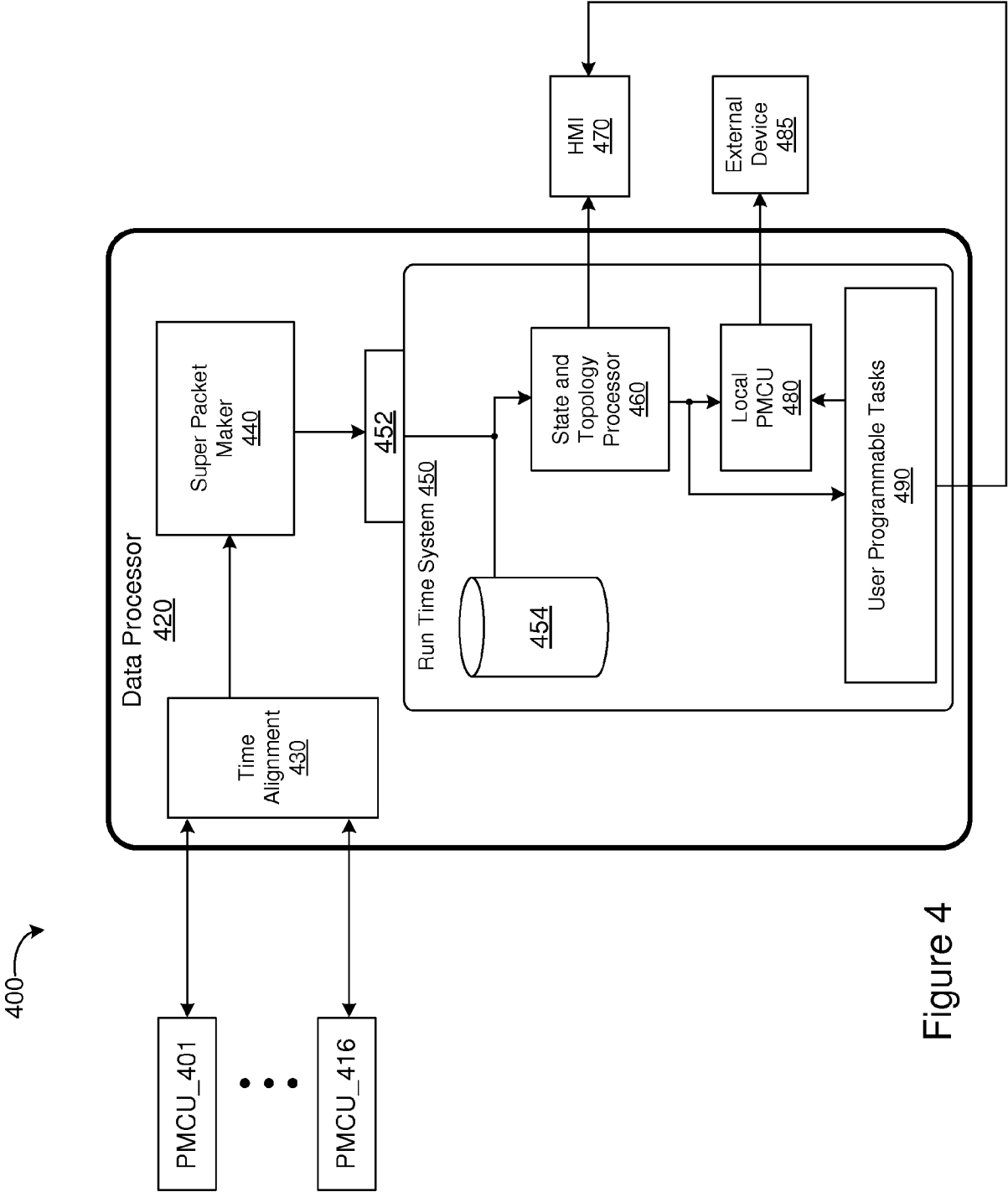


Figure 4

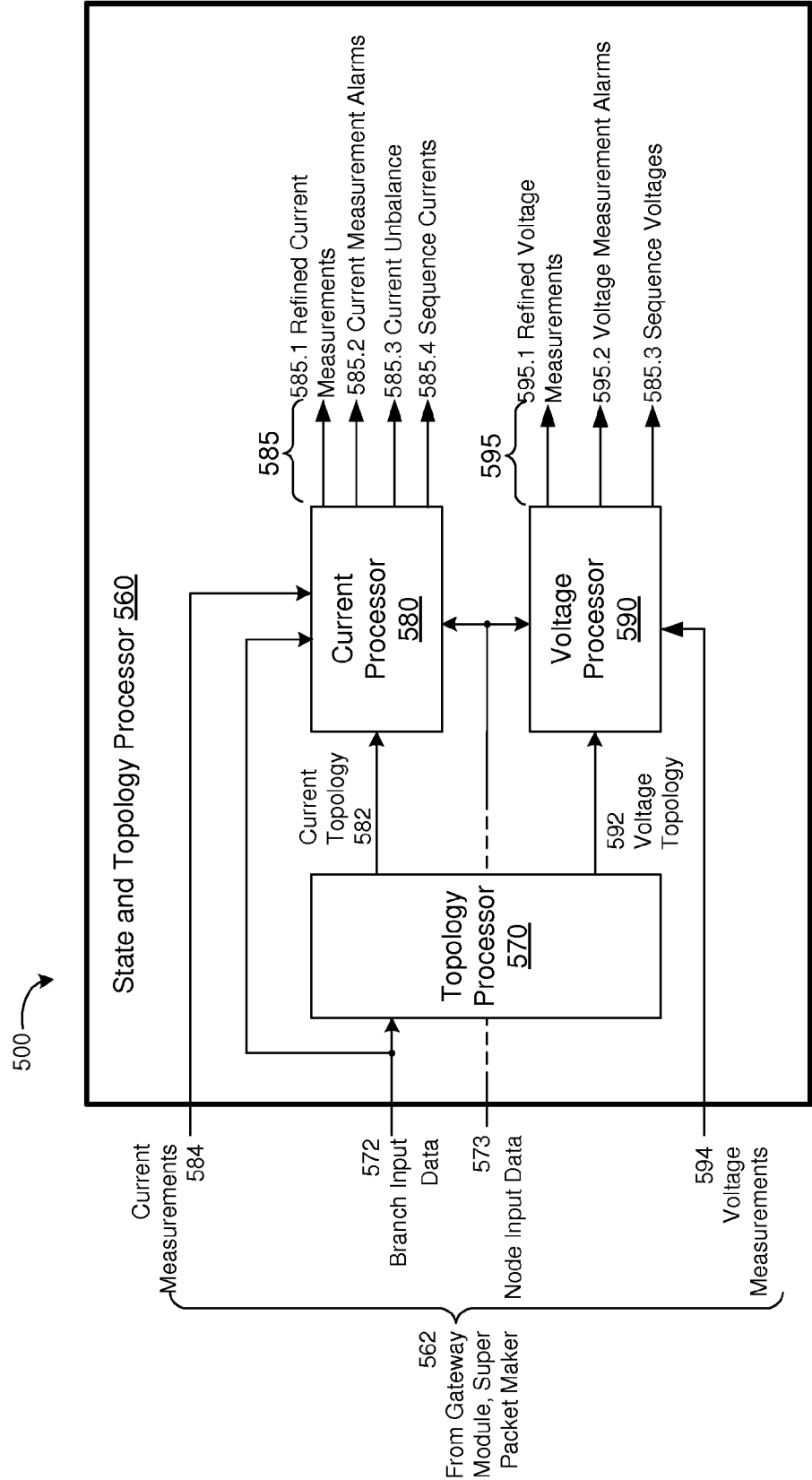


Figure 5

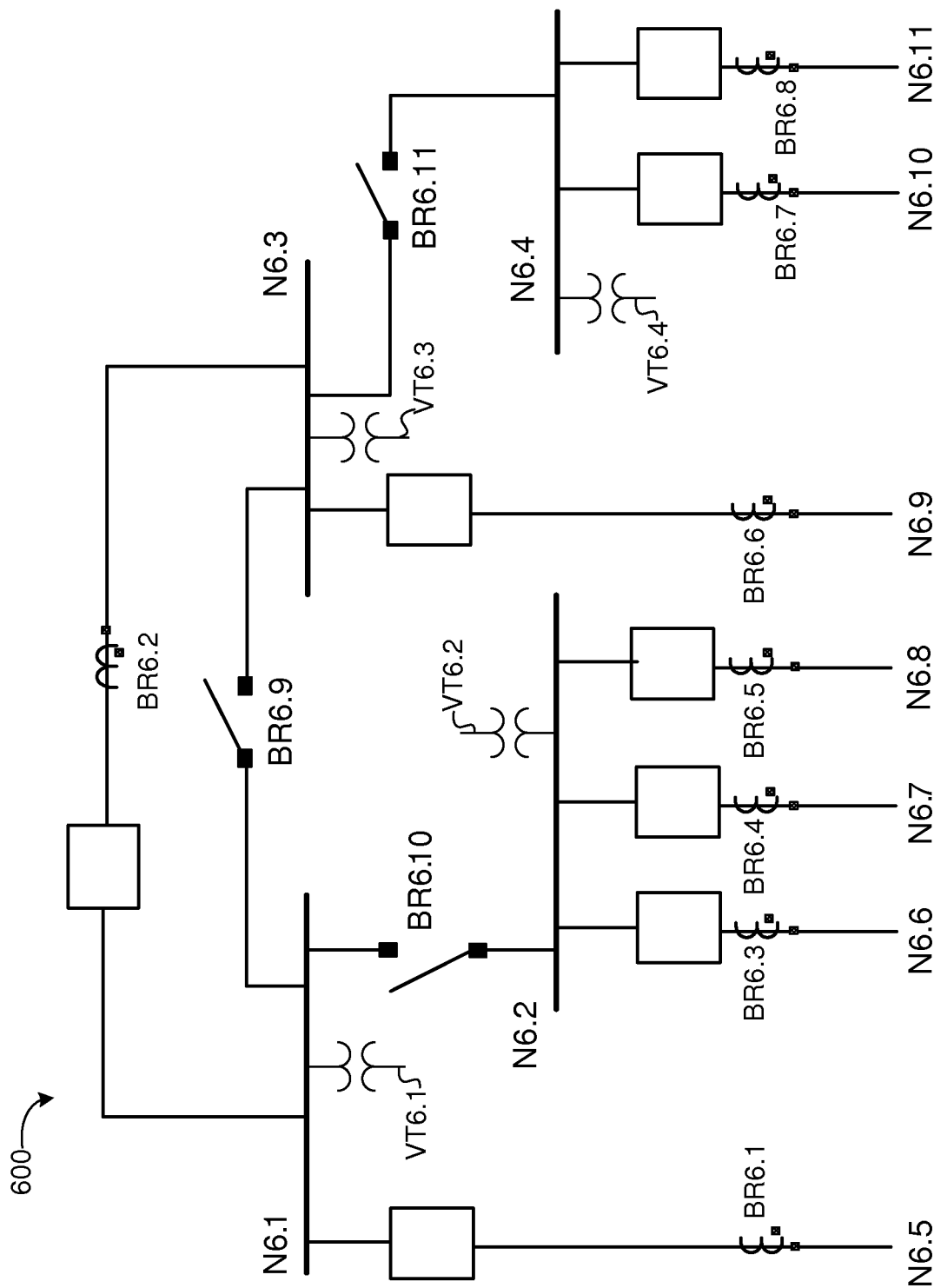


Figure 6

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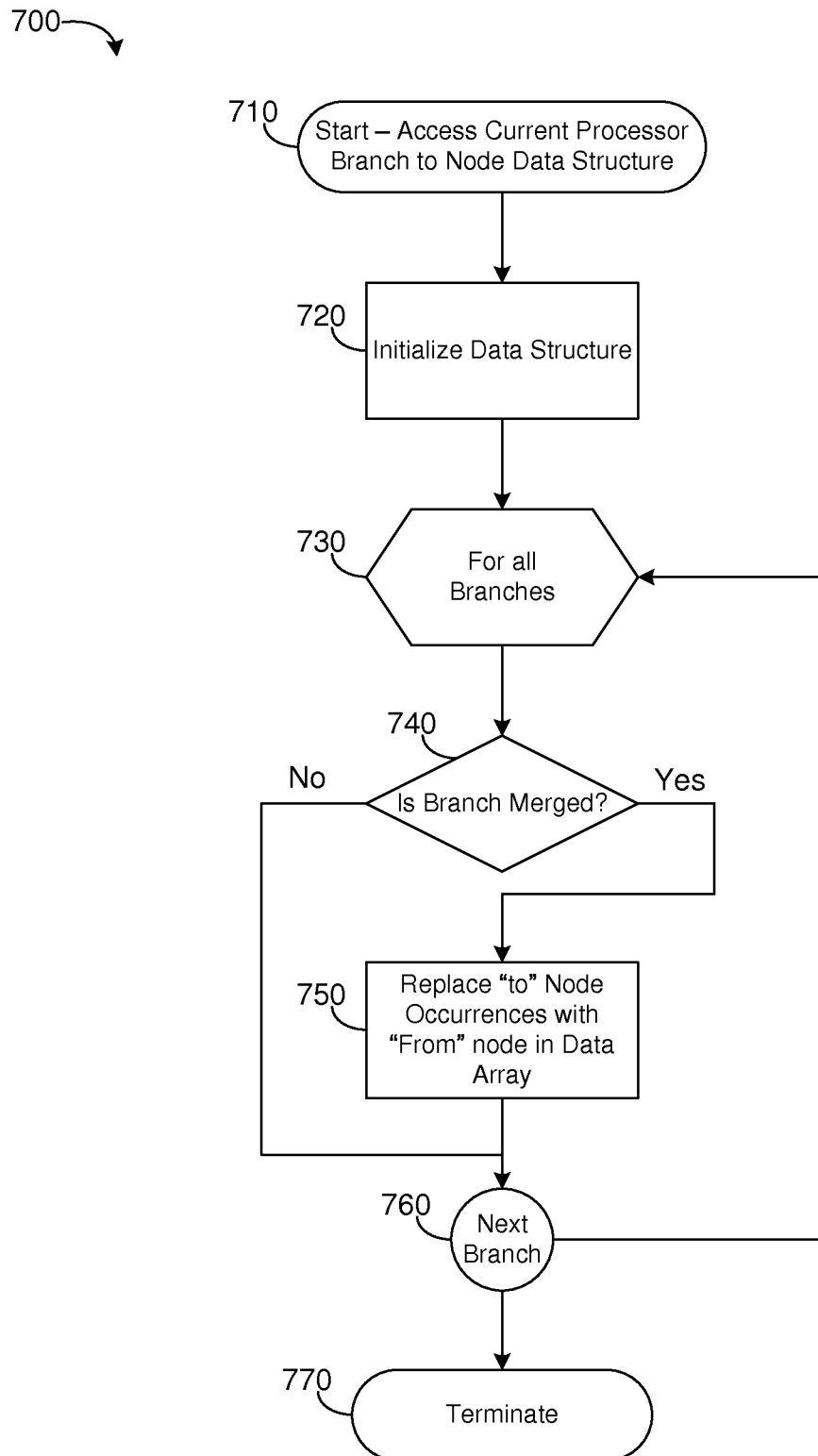


Figure 7A

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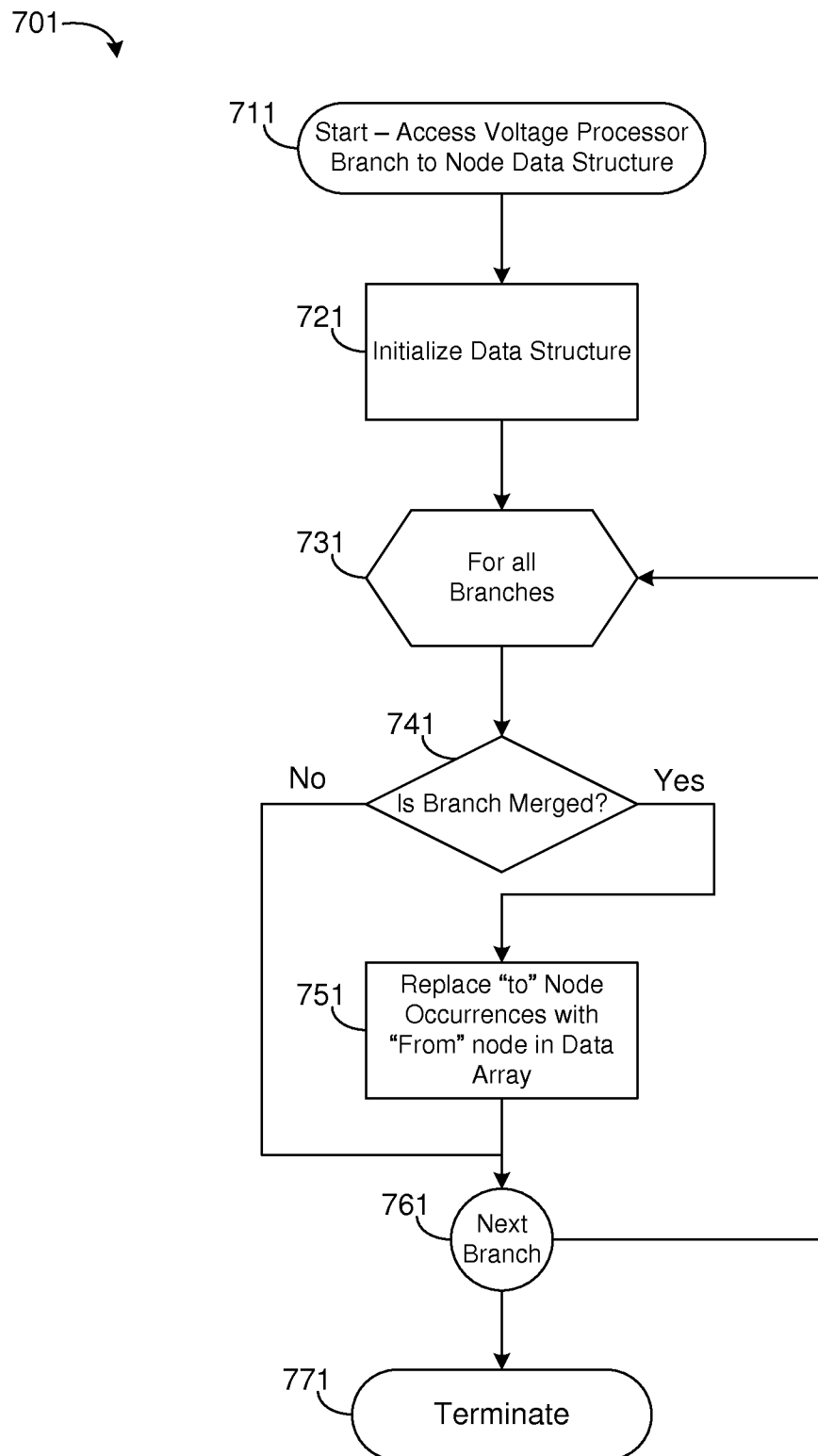


Figure 7B

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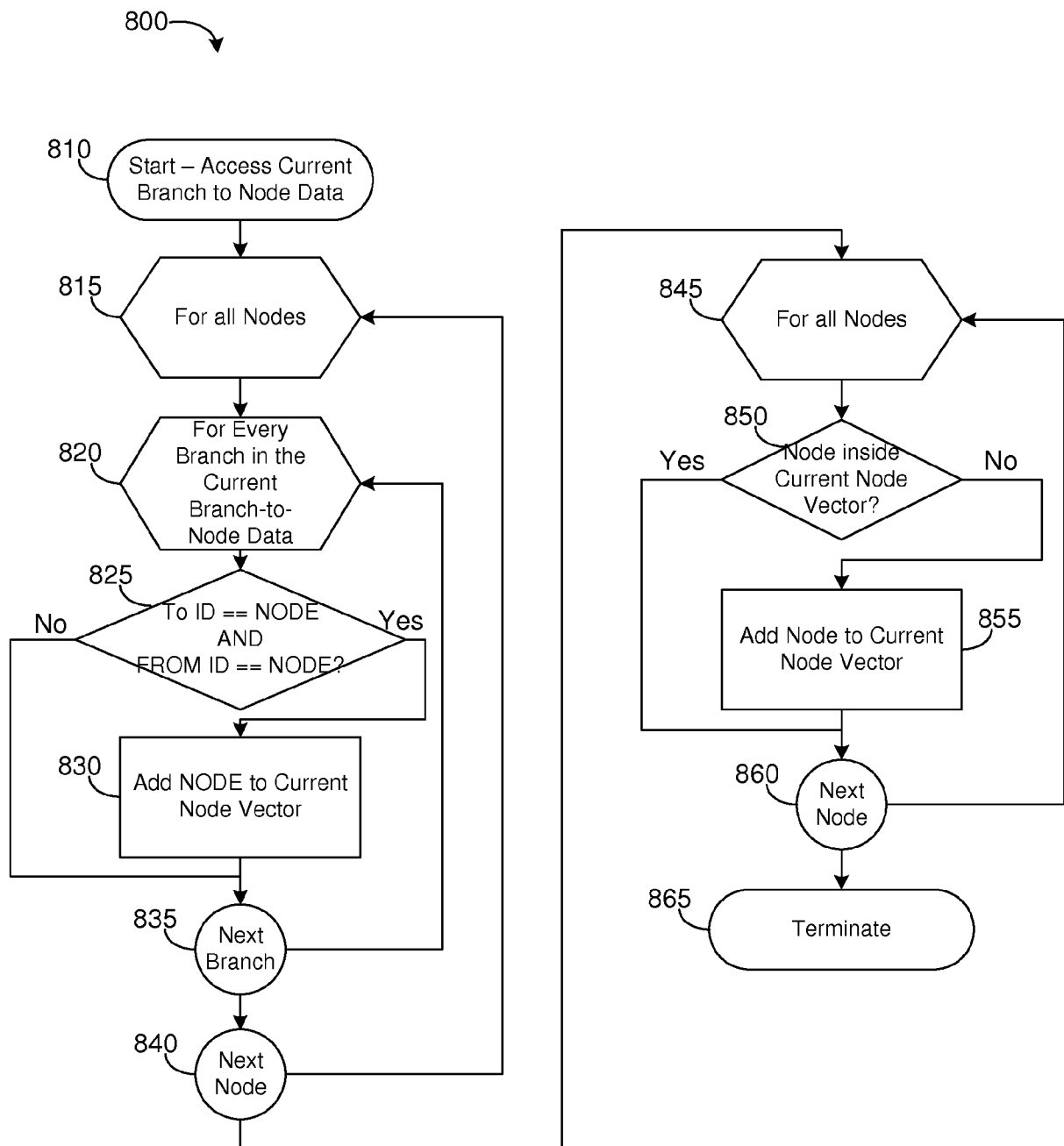


Figure 8A

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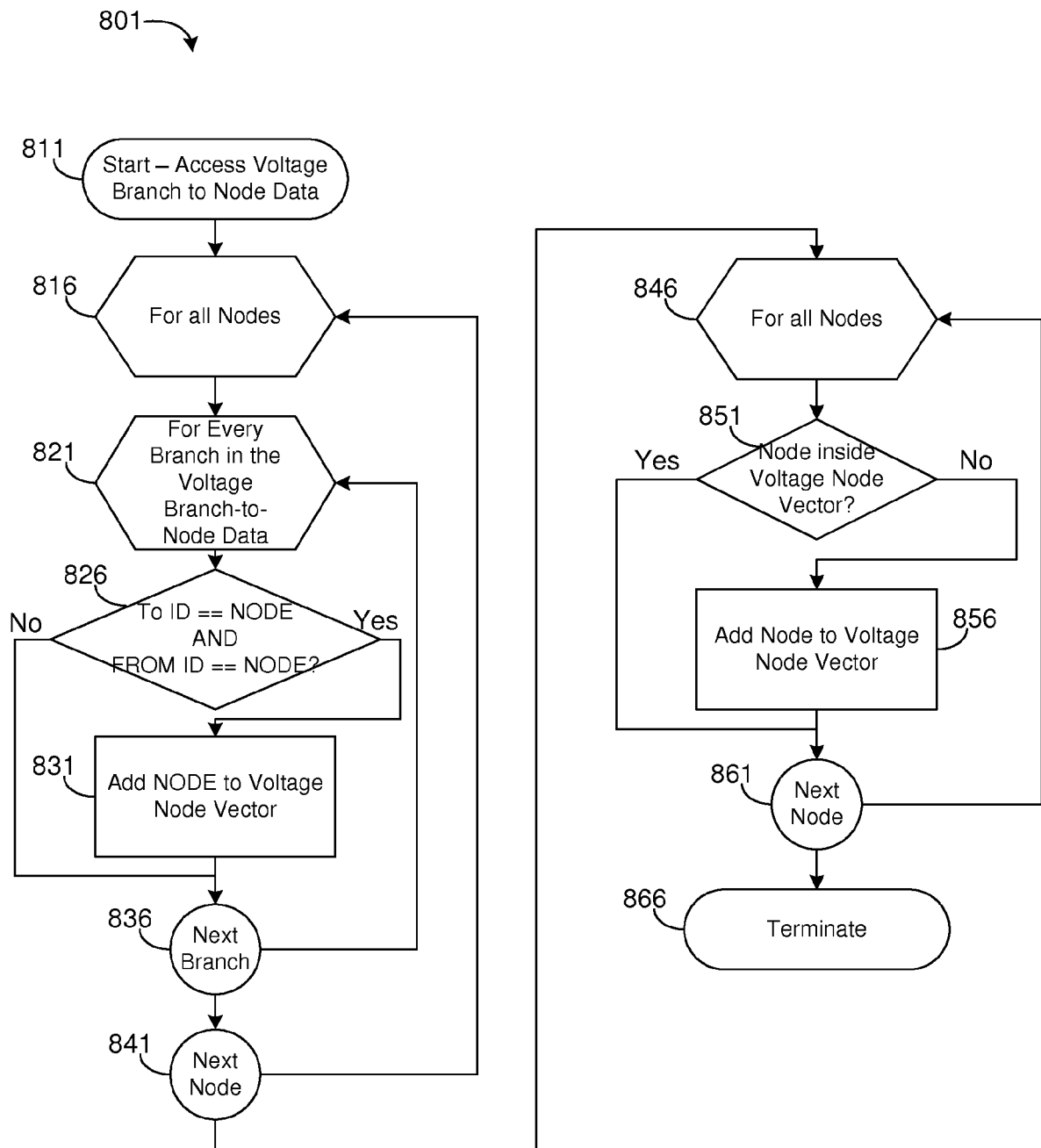


Figure 8B

900 →

903

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From	N6.1	N6.1	N6.2	N6.2	N6.2	N6.3	N6.4	N6.4	N6.1	N6.1	N6.3
To	N6.5	N6.3	N6.6	N6.7	N6.8	N6.9	N6.10	N6.11	N6.3	N6.2	N6.4

905

	BR6.1	BR6.2	BR6.3	BR6.4	BR6.5	BR6.6	BR6.7	BR6.8	BR6.9	BR6.10	BR.11
From	N6.1	N6.1	N6.1	N6.1	N6.1	N6.3	N6.4	N6.4	N6.1	N6.1	N6.3
To	N6.5	N6.3	N6.6	N6.7	N6.8	N6.9	N6.10	N6.11	N6.3	N6.1	N6.4

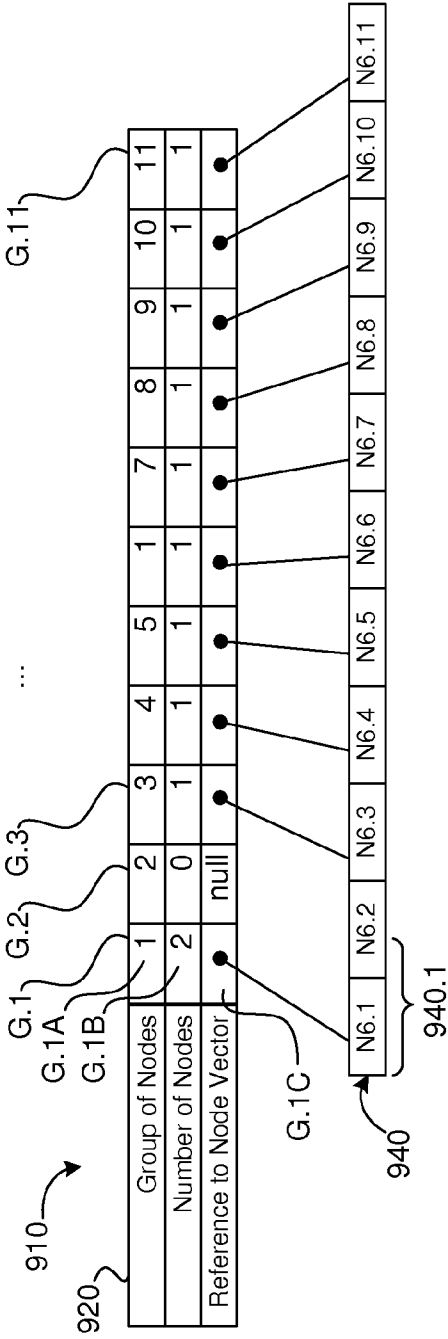


Figure 9

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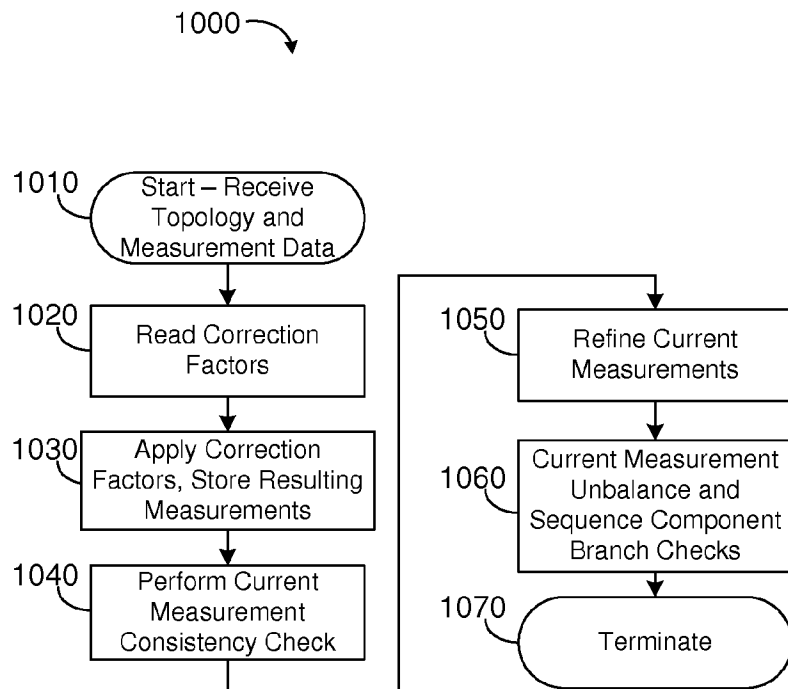


Figure 10

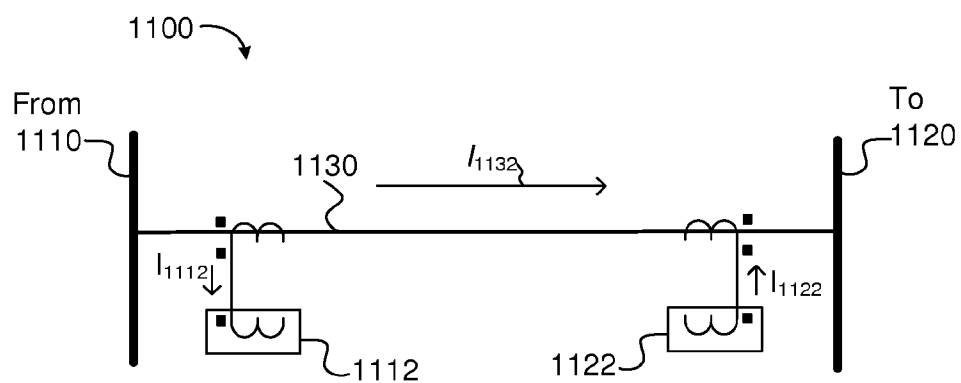


Figure 11

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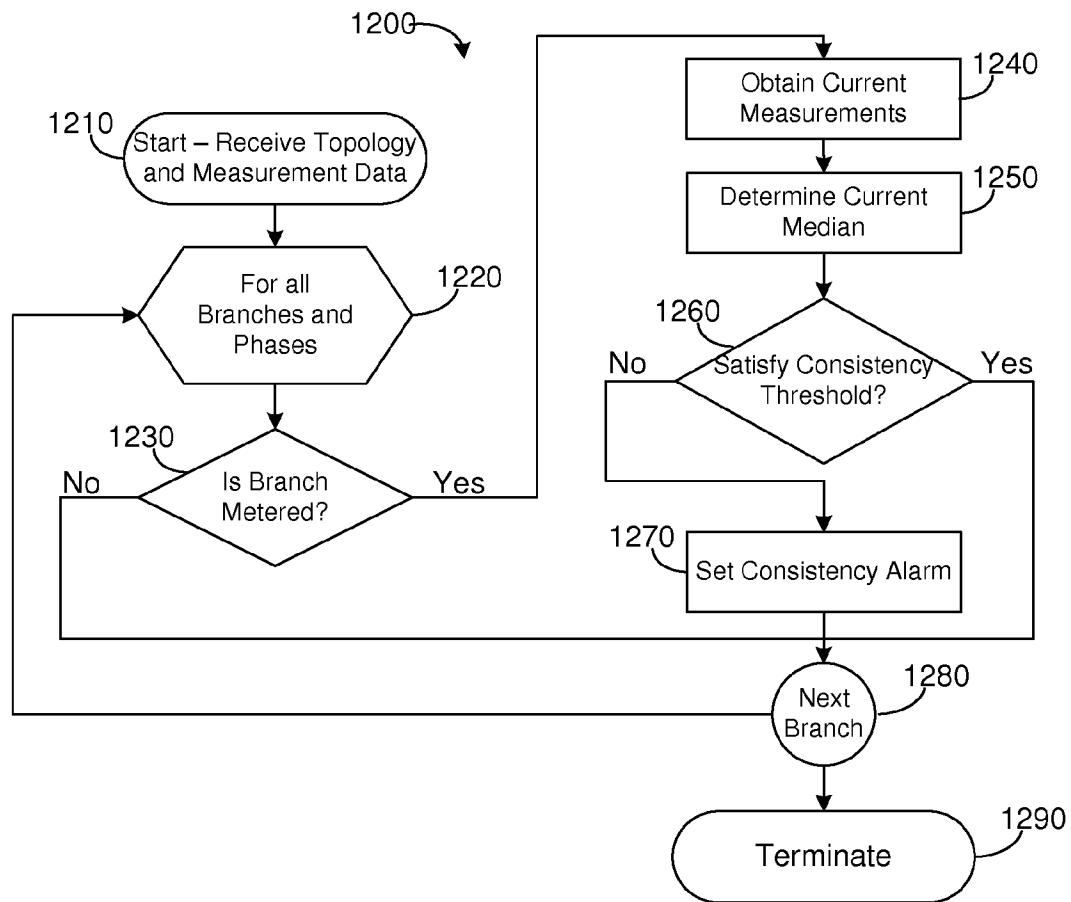


Figure 12A

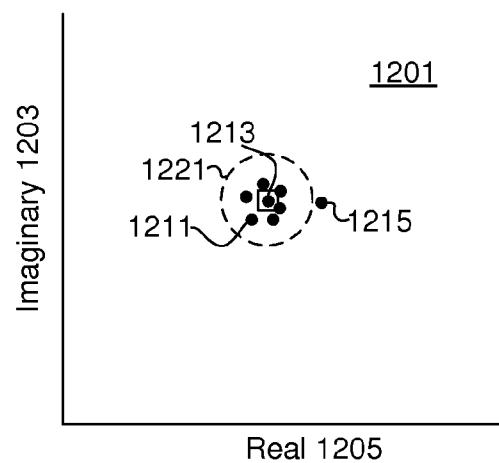


Figure 12B

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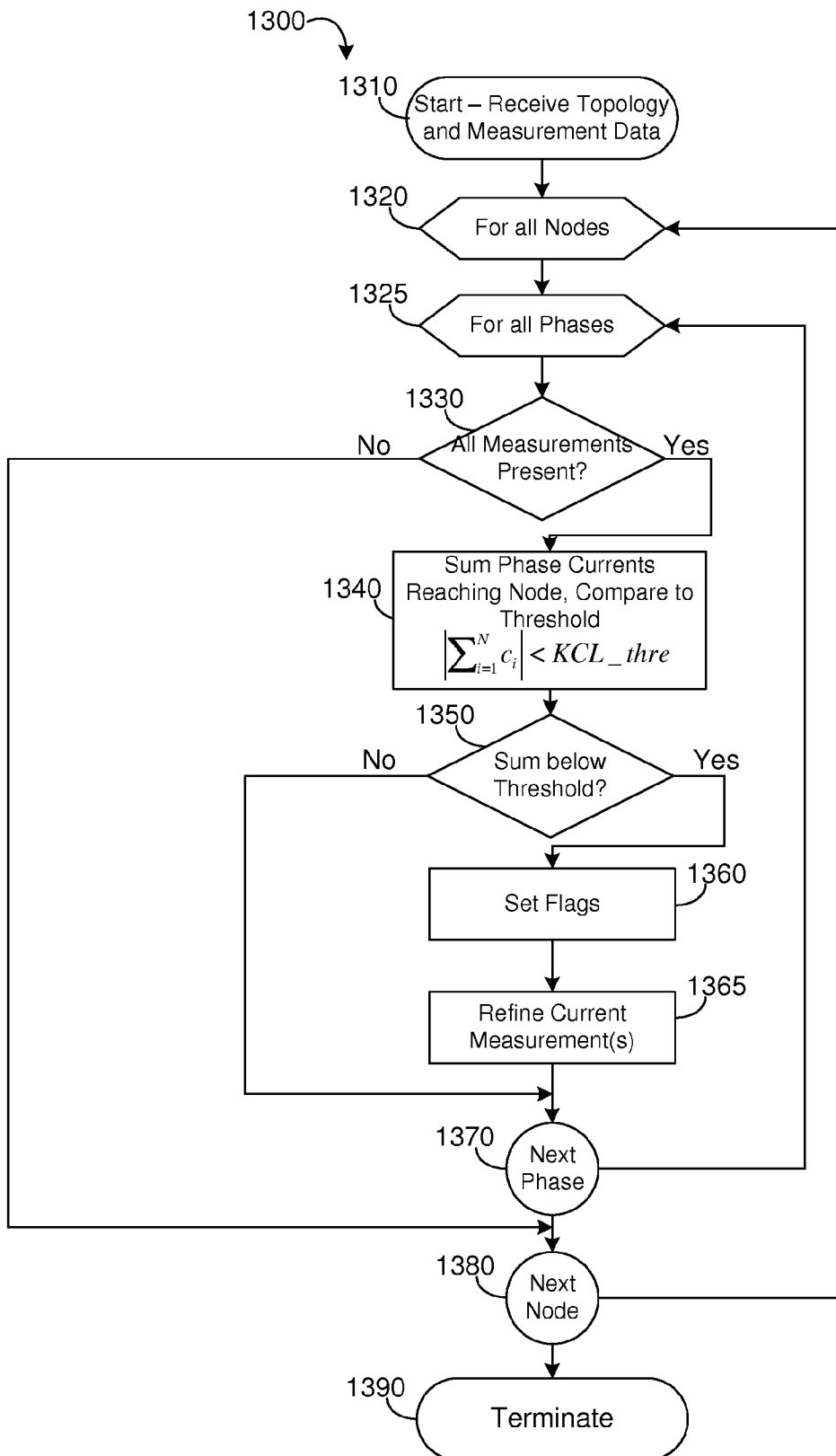


Figure 13A

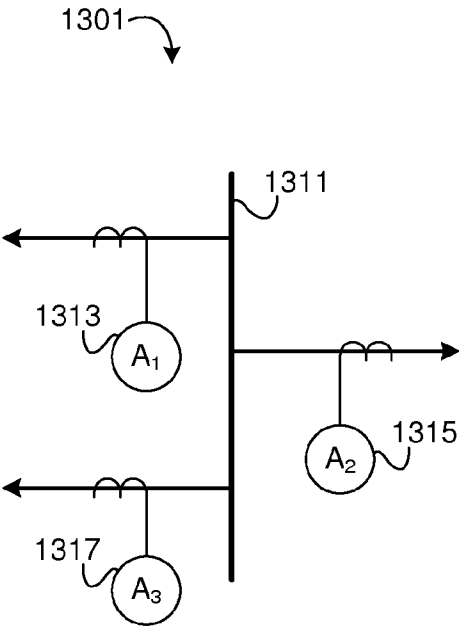


Figure 13B

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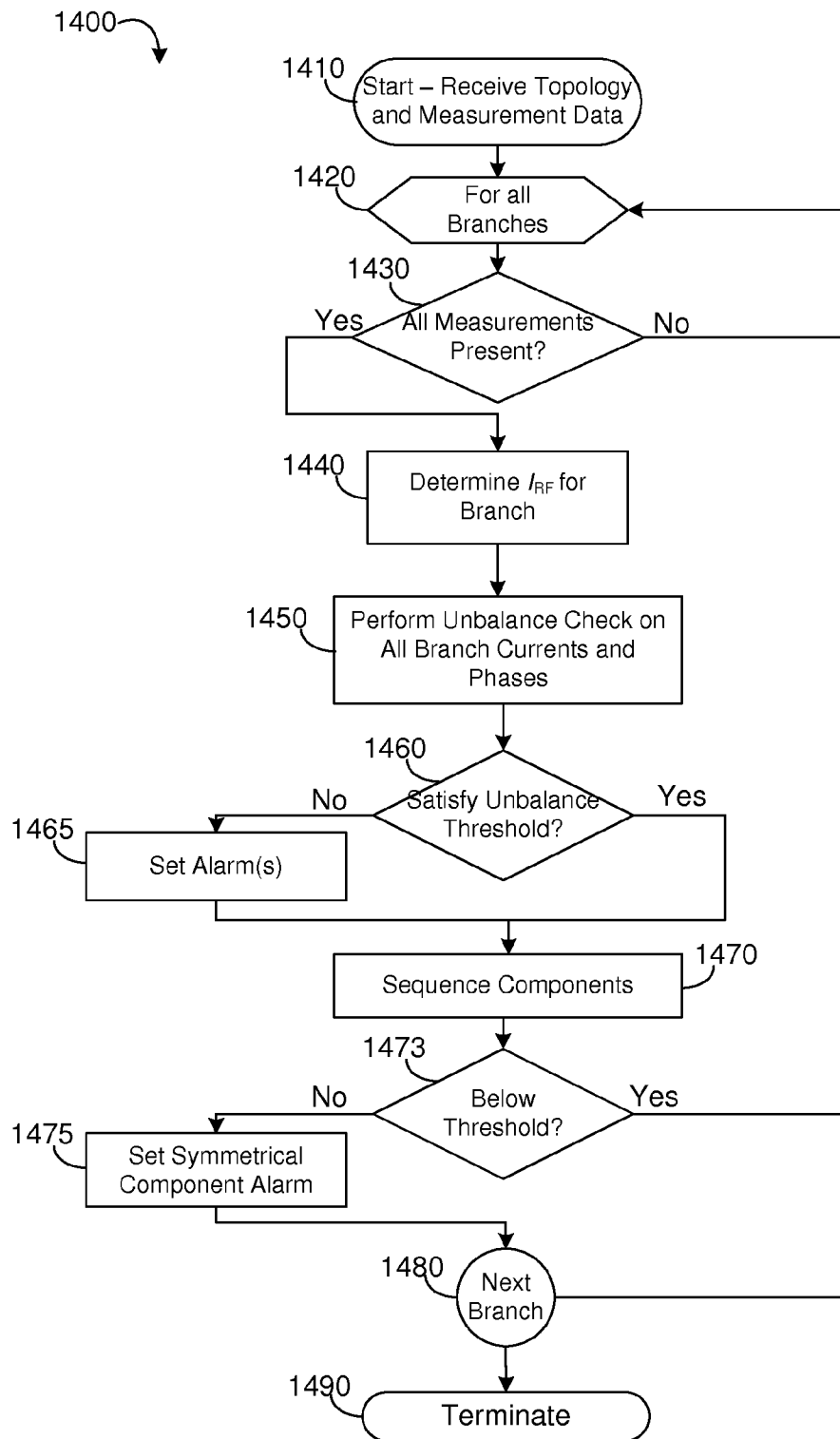


Figure 14

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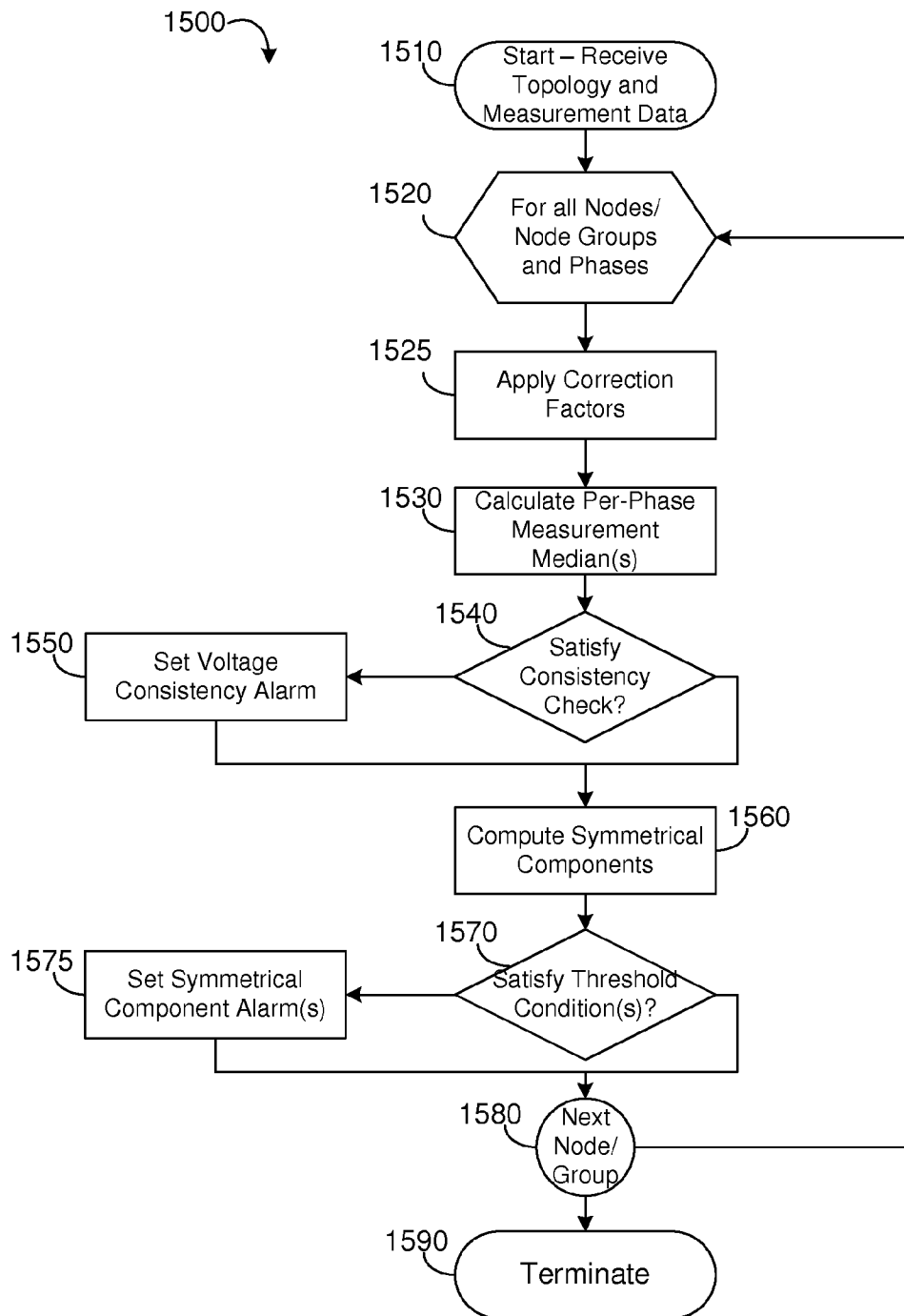


Figure 15

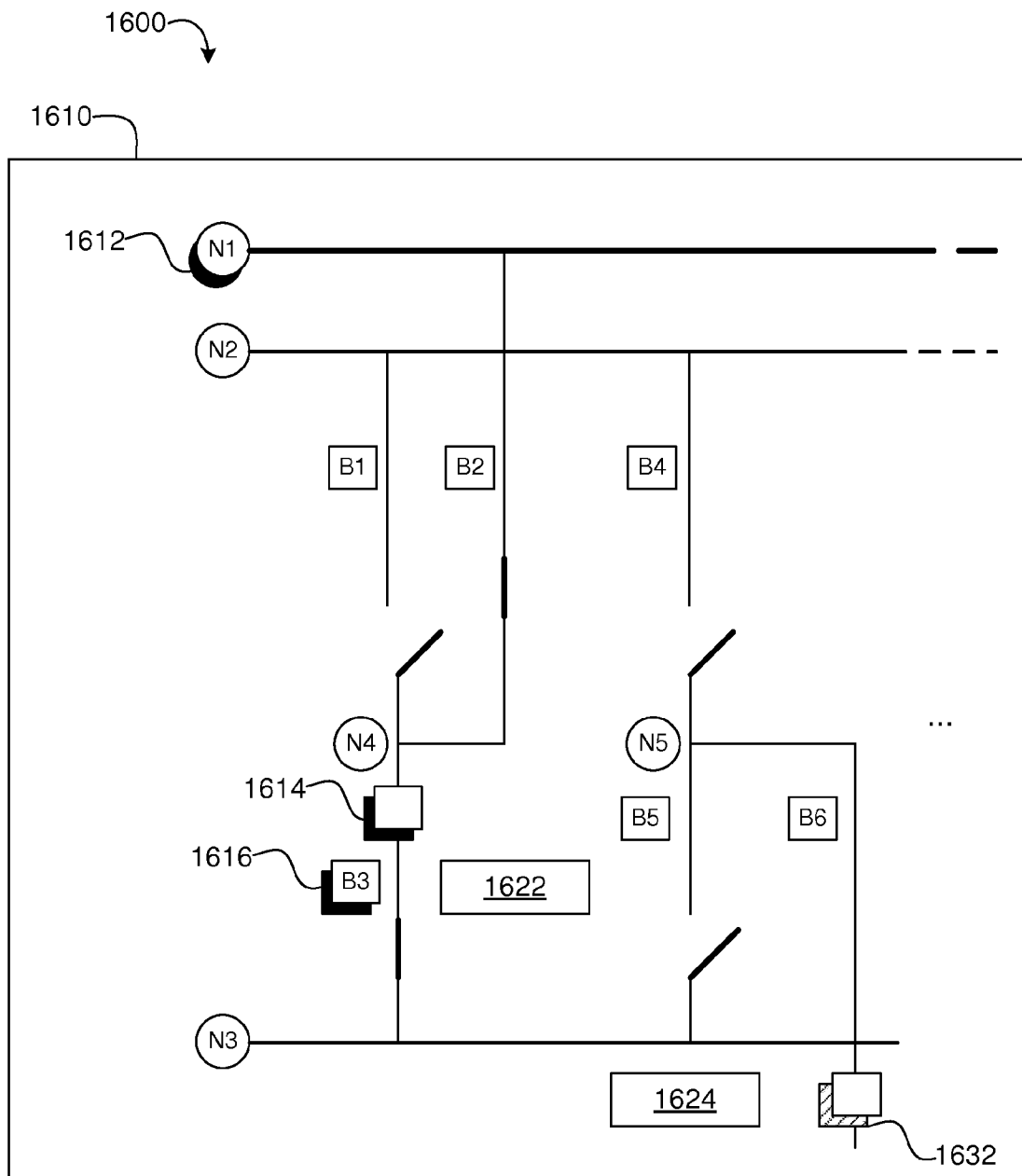


Figure 16

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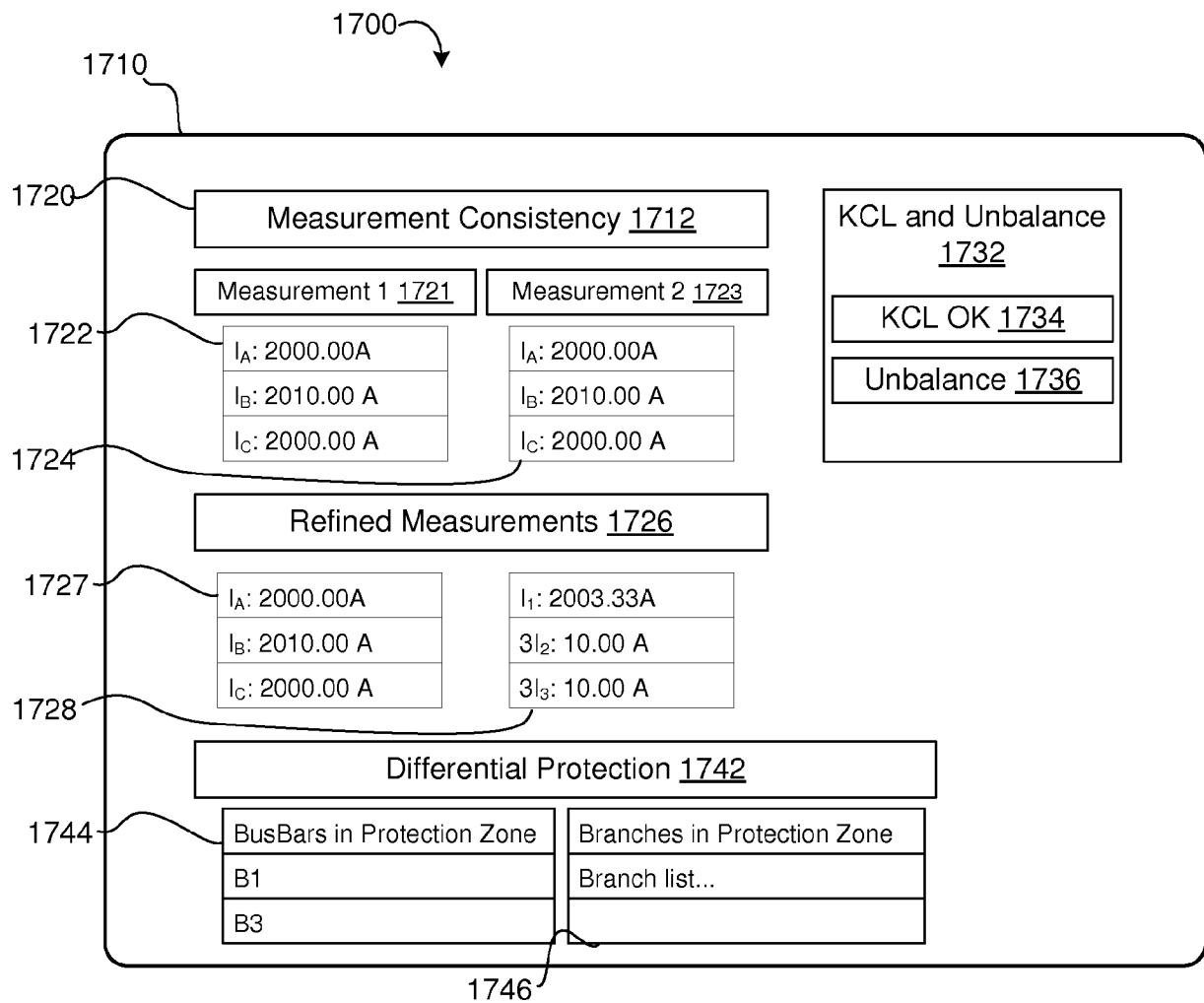


Figure 17

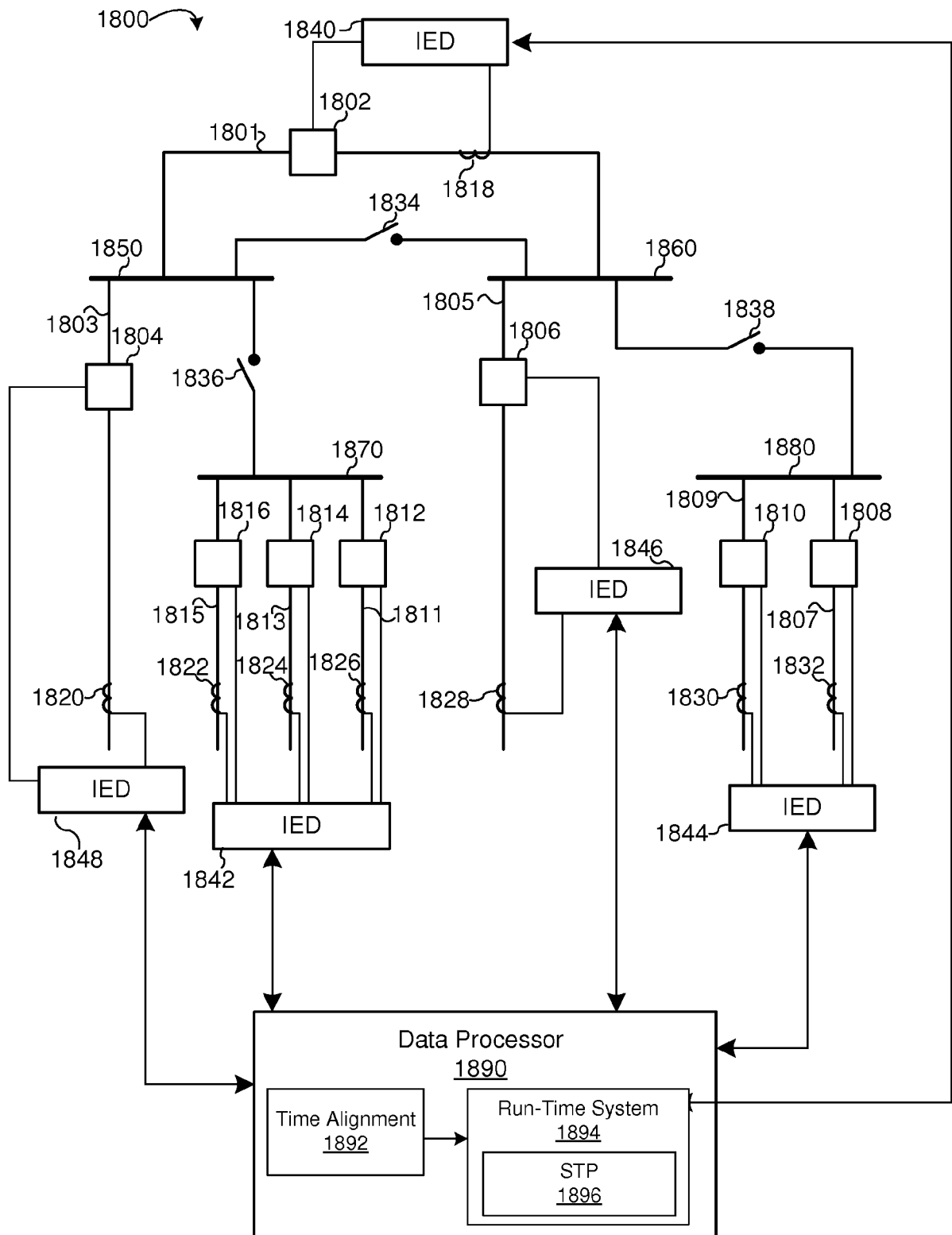


Figure 18

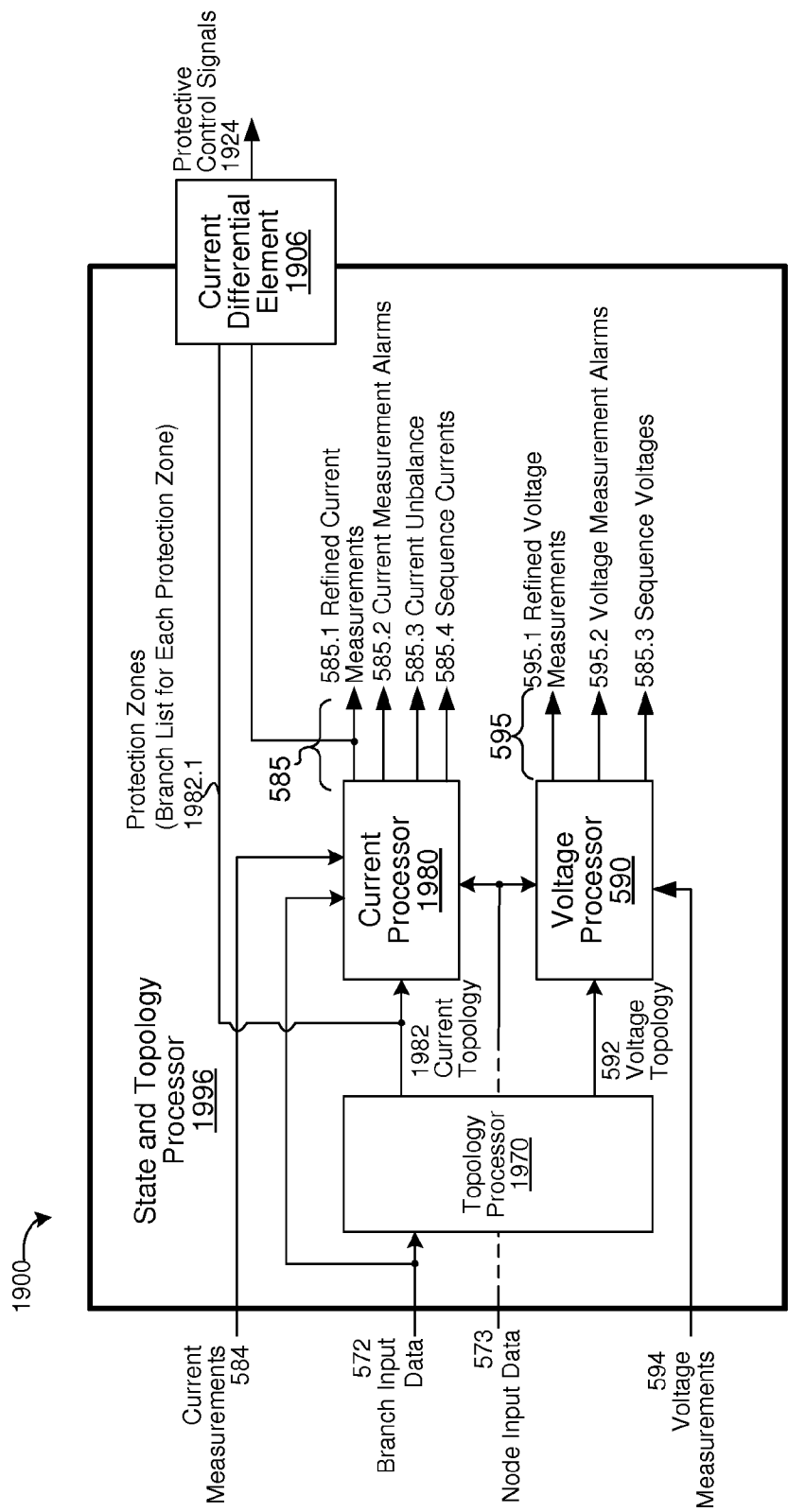


Figure 19

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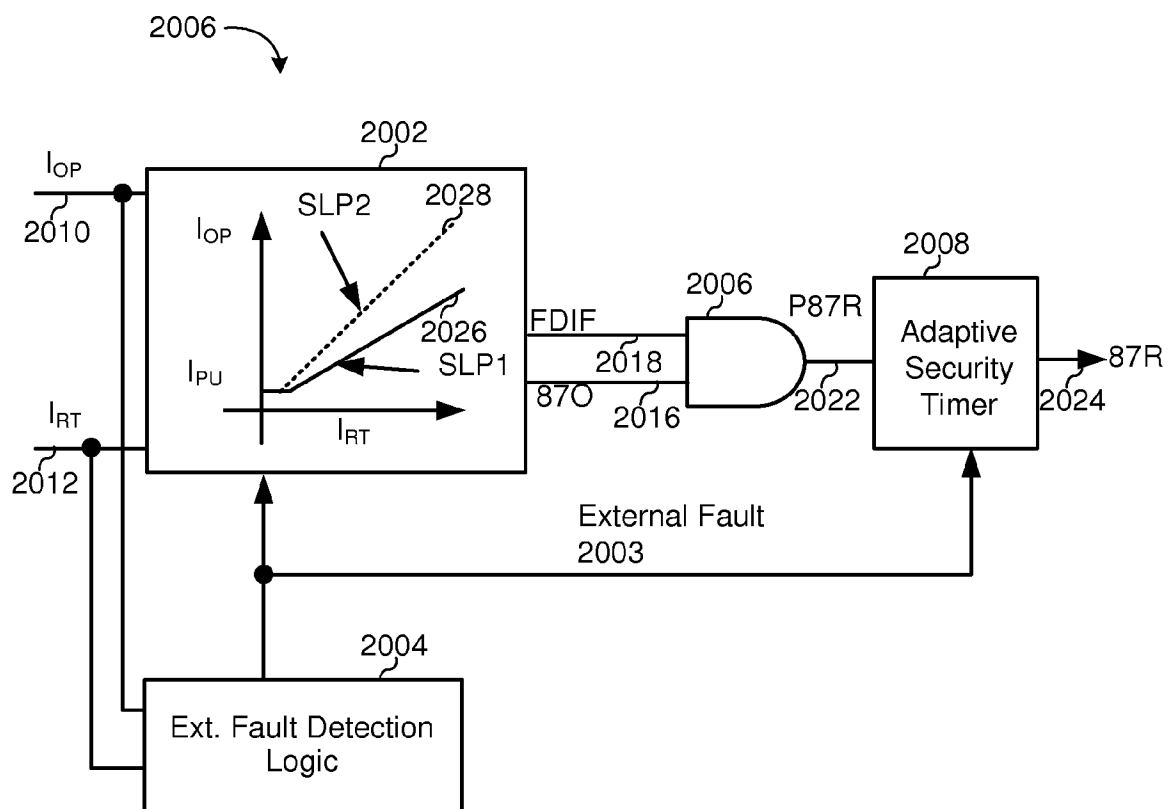


Figure 20

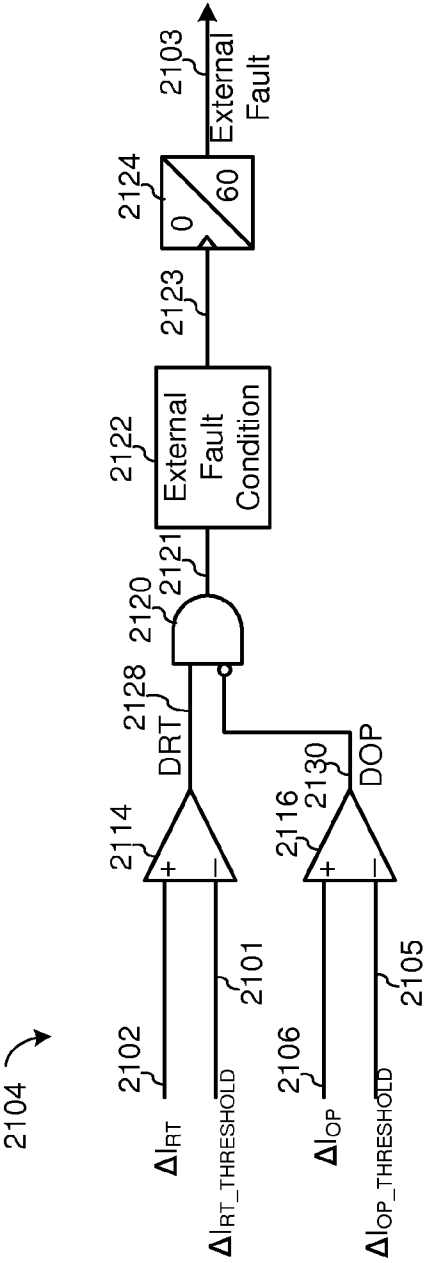


Figure 21

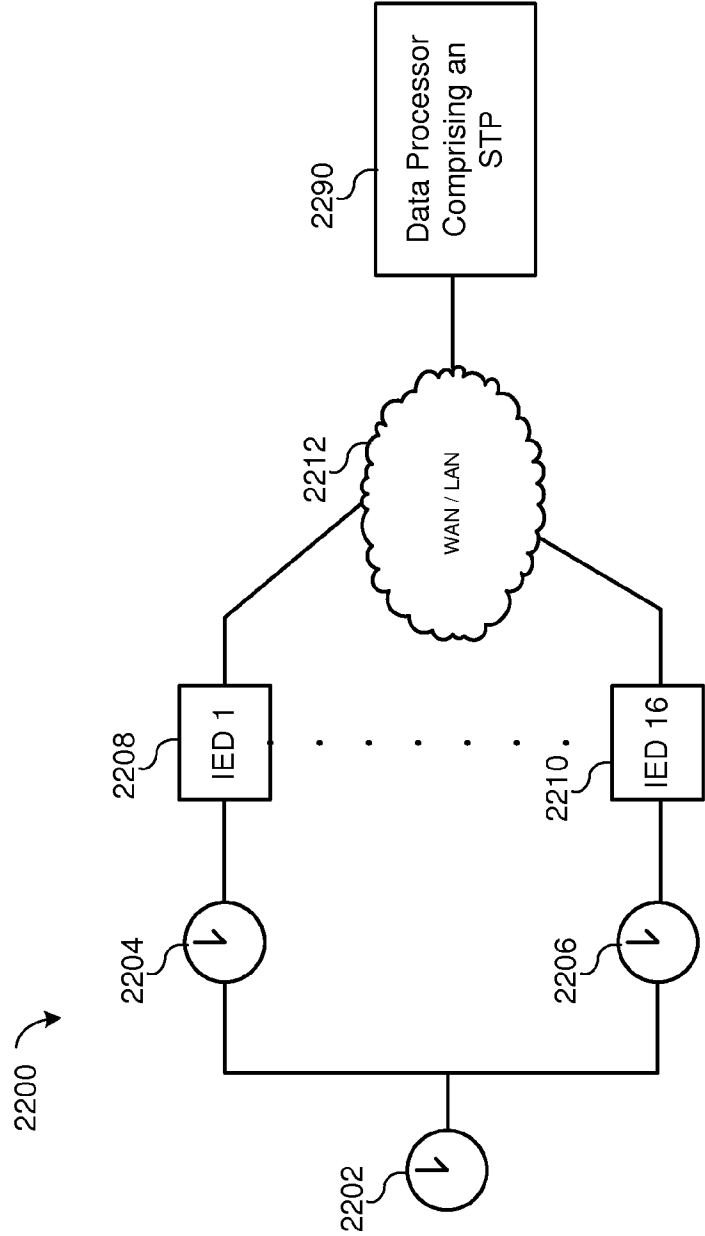


Figure 22

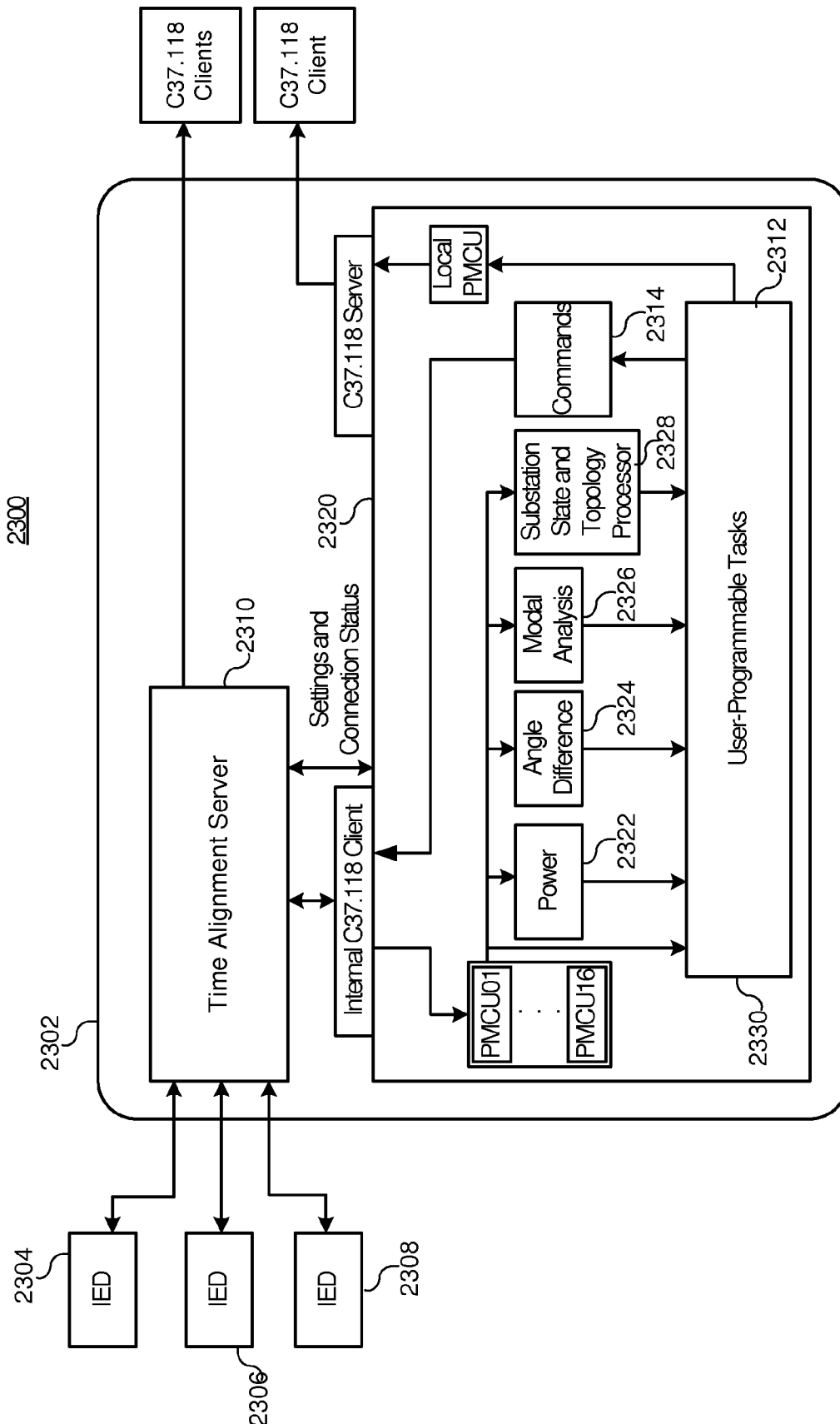


Figure 23

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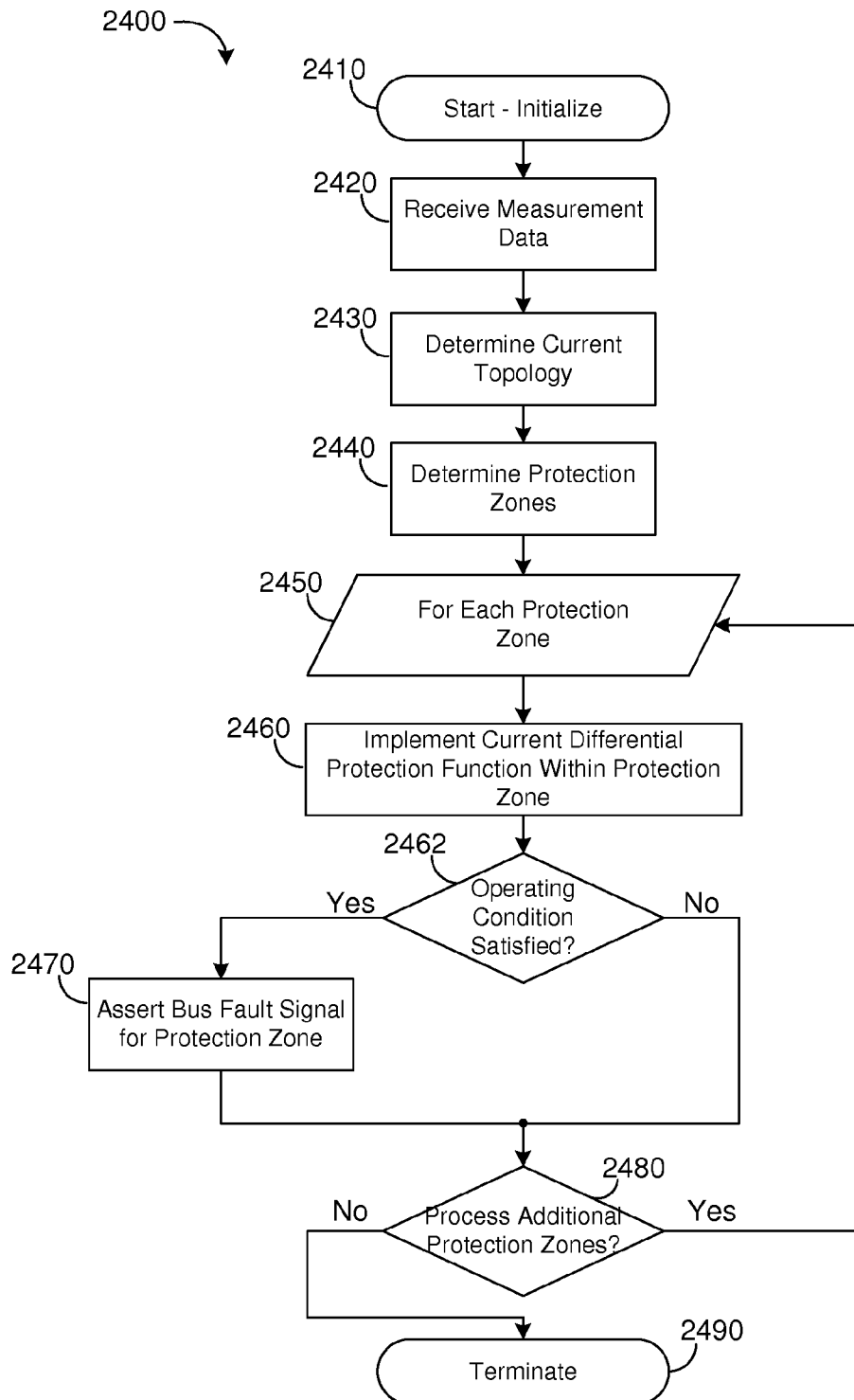


Figure 24

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2009/057533

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H02H 03/00 (2009.01)

USPC - 361/63

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)

IPC(8) - H02H 03/00 (2009.01)

USPC - 361/63

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)

MicroPatent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2007/0086134 A1 (ZWEIGLE et al) 19 April 2007 (19.04.2007) entire document	1-6, 14-15 and 21-22 ----- 7-13, 16-20 and 23
Y	US 6,442,010 B1 (KASZTENNY et al) 27 August 2002 (27.08.2002) entire document	7-13, 16-20 and 23
A	US 2004/0027748 A1 (KOJOVIC et al) 12 February 2004 (12.02.2004) entire document	1-23

☐ Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

06 November 2009

Date of mailing of the international search report

19 NOV 2009

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