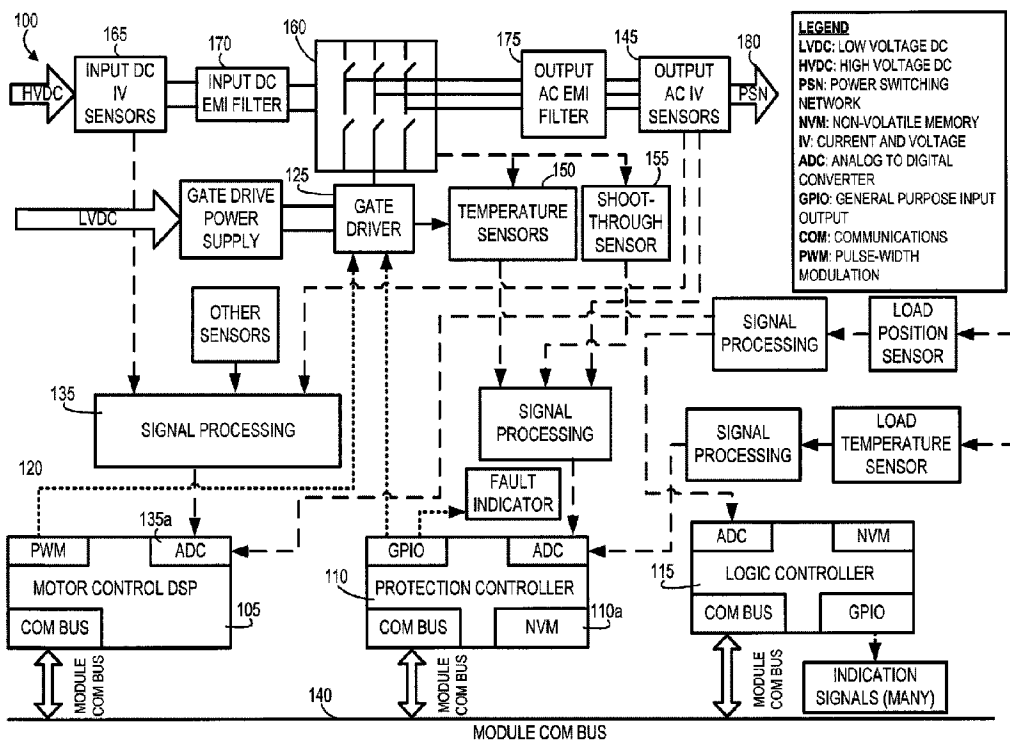




(22) Date de dépôt/Filing Date: 2015/09/21
(41) Mise à la disp. pub./Open to Public Insp.: 2016/06/15
(45) Date de délivrance/Issue Date: 2022/12/13
(30) Priorité/Priority: 2014/12/15 (US14/570,165)

(51) Cl.Int./Int.Cl. *H02J 3/14* (2006.01),
G05B 11/42 (2006.01), *H02J 3/26* (2006.01)
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(54) Titre : SYSTEMES ET METHODES DE REDUCTION DU COURANT BALADEUR ET DU DESEQUILIBRE PHASE-PHASE DANS UN SYSTEME DE CONVERTISSEUR MODULAIRE PARALLELE
(54) Title: SYSTEMS AND METHODS FOR REDUCING CIRCULATING CURRENT AND PHASE-TO-PHASE IMBALANCE IN A PARALLEL MODULAR CONVERTER SYSTEM



(57) **Abrégé/Abstract:**

A system and method for providing power to a vehicle with reduced circulating current and phase-to-phase imbalance is disclosed. The system can include a plurality of parallel module converter for prioritizing and allocating each electrical load to one or more parallel modular converter modules. The system can also comprise a load balancer to ensure that differences in the properties (e.g., impedance) of the parallel modular converter modules do not create circulating currents or phase-to-phase imbalances. The load balancer can monitor the outputs to the plurality of parallel modular converter modules and modify the inputs to equalize, synchronize, or both the outputs.

ABSTRACT

A system and method for providing power to a vehicle with reduced circulating current and phase-to-phase imbalance is disclosed. The system can include a plurality of parallel module converter for prioritizing and allocating each electrical load to one or more parallel modular converter modules. The system can also comprise a load balancer to ensure that differences in the properties (e.g., impedance) of the parallel modular converter modules do not create circulating currents or phase-to-phase imbalances. The load balancer can monitor the outputs to the plurality of parallel modular converter modules and modify the inputs to equalize, synchronize, or both the outputs.

SYSTEMS AND METHODS FOR REDUCING CIRCULATING CURRENT AND PHASE-TO-PHASE IMBALANCE IN A PARALLEL MODULAR CONVERTER SYSTEM

5

BACKGROUND

Embodiments of the present disclosure relate generally to power management and specifically to a system and method for controlling phase-to-phase imbalances and reducing the circulating current in a parallel modular converter system.

10 Modern vehicles use a large number of electronics, motors, heaters, and other electrically driven equipment. Electric motors, in particular, are ubiquitous in modern vehicles, including aircraft, and power everything from hydraulic pumps to cabin fans. Conventionally, each of these electric motors has been driven by an independent motor controller. Each motor controller is sized to be able to carry the maximum
15 amount of current required to power its respective motor at full power for an extended period of time (and generally, includes some additional capacity for safety) without overheating or malfunctioning.

As a result, each aircraft carries an excessive number of motor controllers, each of which is oversized and underutilized a majority of the time. In other words,
20 the motor controller includes enough capacity to run the motor at full power for an extended period of time plus a safety margin, but motors are rarely, if ever, run at full capacity. This is because the motors themselves have some safety margin built in and because, a majority of the time, the motors are operating in a lower demand regime (e.g., the cabin fan is not always on "High"). In addition, some motors are
25 only used occasionally, or during specific flight segments, and are unused the remainder of the time. As a result, many of an aircraft's complement of heavy, expensive motor controllers spend a majority of their service life either inactive or significantly below their rated power outputs.

What is needed, therefore, is a system architecture that enables the use of
30 multiple, modular, assignable, dynamically reconfigurable parallel motor controllers

that can work alone or in parallel with other parallel motor controllers to meet power control needs. The system should enable one or more parallel controllers to be assigned to each active electrical load in the aircraft, as necessary, to meet existing power demands. The system should enable the use of such parallel controllers, while minimizing phase-to-phase imbalances and reducing circulating current. It is to such a system that embodiments of the present disclosure are primarily directed.

SUMMARY

It should be appreciated that this Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to be used to limit the scope of the claimed subject matter.

Embodiments of the present disclosure relate to systems and methods related to a modular power distribution and power conversion system for electrical loads. The system can include a plurality of parallel modular converter modules ("modules") linked to form a parallel modular converter ("converter"). The system and method can operate multiple modules simultaneously and in parallel, while maintaining substantially equal output from each module.

In one embodiment, there is provided a system for powering a plurality of electrical loads. The system includes a first parallel modular converter module having a first input and a first output configured to provide a first alternating current (AC) output to a first load of the plurality of electrical loads. The system further includes a second parallel modular converter module having a second input and a second output configured to provide a second AC output to the first load. The system further includes a load balancer connected to the first input, the second input, the first output, and the second output. The load balancer is configured to compare the first output from the first parallel modular converter module with the second output from the second parallel modular converter module. The load balancer is further configured to modify, upon determining an imbalance exists between the first output and the second output, an associated control algorithm for one or both of the first parallel

modular converter module and the second parallel modular converter module to thereby equalize the first output and the second output. The system further includes a controller configured to generate one or more control signals corresponding to one or more selected control algorithms of a plurality of control algorithms, wherein the plurality of control algorithms includes the associated control algorithm. The system further includes a control switching network comprising a plurality of switching elements and configured to transmit a first control signal of the one or more control signals to apply the associated control algorithm to the first parallel modular converter module and to the second parallel modular converter module when coupled with the first load.

In another embodiment, there is provided a parallel modular converter. The parallel modular converter includes a first parallel modular converter module configured to provide a first alternating current (AC) output and connected to a module communications bus, and a second parallel modular converter module configured to provide a second AC output and connected to the module communications bus. The parallel modular converter includes a master logic controller configured to assign the first parallel modular converter module and the second parallel modular converter module to power a first load. The parallel modular converter further includes a master communications controller connected to the module communications bus and configured to route messages between the master logic controller and the first parallel modular converter module and the second parallel modular converter module, whereby a calculated ideal load sharing value is applied to control the first AC output and to control the second AC output. The parallel modular converter further includes a load balancer connected to a respective input and a respective output of each of the first parallel modular converter module and the second parallel modular converter module. The load balancer is configured to determine, responsive to application of the calculated ideal load sharing value, that an imbalance exists between the first AC output and the second AC output, and modify, responsive to determining that the imbalance exists, an associated control algorithm for one or both of the first parallel modular converter module and the second parallel converter module to thereby equalize the first AC output and the

second AC output. The parallel modular converter further includes a motor control system configured to generate one or more control signals according to one or more selected control algorithms of a plurality of control algorithms, wherein the plurality of control algorithms includes the associated control algorithm. The parallel modular converter further includes a control switching network comprising a plurality of switching elements and is configured to transmit a first control signal of the one or more control signals to apply the associated control algorithm to the first parallel modular converter module and to the second parallel modular converter module when coupled with the first load.

In another embodiment, there is provided a method for balancing outputs between a plurality of parallel modular converter modules. The method involves receiving, at a system controller, a request from a vehicle controller to power a first load, and calculating, using a load balancer coupled with the system controller, a first number of parallel modular converter modules sufficient to power the first load. The method further involves placing in parallel, using a master logic controller coupled with the load balancer, the first number of modules selected from a plurality of parallel modular converter modules. The method further involves configuring, responsive to a first control signal from the system controller, a control switching network to transmit, from a plurality of received control signals corresponding to a plurality of control algorithms, a second control signal to the selected modules to apply a first control algorithm thereto, the first control algorithm selected from the plurality of control algorithms, the control switching network comprising a plurality of switching elements and arranged between the system controller and the load balancer. The method further involves sensing, using the load balancer, a respective output from each of the selected modules, and modifying, using the load balancer and upon determining an imbalance exists between the respective outputs of the selected modules, the first control algorithm for one or more individual modules of the selected modules to equalize the outputs of the selected modules.

In another embodiment, there is provided a parallel modular converter. The parallel modular converter includes a first parallel modular converter module

configured to provide a first alternating current "AC" output and connected to a module communications bus, and a second parallel modular converter module configured to provide a second AC output and connected to the module communications bus. The parallel modular converter further includes a master communications controller connected to the module communications bus and a master logic controller to route messages therebetween, and a load balancer connected to an input and an output of both the first parallel modular converter module and the second parallel modular converter module. The load balancer is configured to calculate the number of parallel converter modules required to power a first load. The master logic controller is configured to place the first parallel modular converter module and the second parallel modular converter module in parallel using a power switching network and to assign the first load to the first parallel modular converter module and the second parallel modular converter module, the module communications bus connecting the first parallel modular converter module and the second parallel modular converter module. The load balancer is configured to modify the input to the first parallel modular converter module to equalize the output of the first parallel modular converter module with the output of the second parallel modular converter module.

In another embodiment, there is provided a method for balancing outputs between a plurality of parallel modular converter modules. The method involves receiving a request to power a first load from a vehicle controller at a system controller, and calculating a number of parallel modular converter modules required to power the first load with a load balancer. The method further involves placing the calculated parallel modular converter modules required to power the first load in parallel with a master logic controller, and sensing an output from each of the calculated parallel modular converter modules with the load balancer. The method further involves modifying an input signal to one or more of the calculated parallel modular converter modules with the load balancer such that the output of each of the calculated parallel modular converter modules is equal.

The features, functions, and advantages that have been discussed can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments, further details of which can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is an electrical schematic depicting a parallel modular converter module (“module”) for use in a parallel modular converter in a high voltage DC input application, in accordance with some embodiments of the present disclosure.

Fig. 2 is an electrical schematic depicting a module for use in a parallel modular converter in an AC input application, in accordance with some embodiments of the present disclosure.

5 Figs. 3A-3C are electrical schematics depicting a parallel module converter (“converter”) using multiple modules in a high voltage DC current regime, in accordance with some embodiments of the present disclosure.

Fig. 4 is an electrical schematic depicting an output configuration, in accordance with some embodiments of the present disclosure.

10 Fig. 5 is an electrical schematic depicting an alternative module with shared controllers in a high voltage DC input application, in accordance with some embodiments of the present disclosure.

Figs. 6A-6C are electrical schematics depicting an alternative converter in a high voltage DC input application, in accordance with some embodiments of the present disclosure.

15 Fig. 7 is an electrical schematic depicting a power switching network, in accordance with some embodiments of the present disclosure.

Fig. 8 is an electrical schematic depicting a parallel modular converter, in accordance with some embodiments of the present disclosure.

20 Figs. 9A-9C are electrical schematics depicting an alternative converter, in accordance with some embodiments of the present disclosure.

Fig. 10 is an electrical schematic depicting an overall system architecture for the converter, in accordance with some embodiments of the present disclosure.

25 Fig. 11 is a detailed electrical schematic depicting a control switching network and a power switching network of Fig. 10, in accordance with some embodiments of the present disclosure.

Fig. 12 is a flowchart depicting a method of distributing power, in accordance with some embodiments of the present disclosure.

Fig. 13 is a flowchart depicting a method for reapportioning loads to a plurality of modules, in accordance with some embodiments of the present disclosure.

Fig. 14 is a flowchart depicting a method for equalizing current between parallel modules, in accordance with some embodiments of the present disclosure.

5 Fig. 15 is an electrical schematic depicting an overall system architecture for a converter with a load balancer, in accordance with some embodiments of the present disclosure.

Each figure shown in this disclosure shows a variation of an aspect of the embodiment presented, and only differences will be discussed in detail.

10

DETAILED DESCRIPTION

Embodiments of the present disclosure relate generally to power distribution and power conversion systems and more particularly to a parallel modular converter for distributing electrical loads without the need for individual controllers at each electrical load. The converter can utilize a load balancer to monitor the inputs and outputs to each parallel modular converter module in the parallel module converter to match the output currents. This can result in reduction of circulating current and phase-to-phase imbalances, among other things.

To simplify and clarify explanation, the disclosure is described herein as a system for allocating power on an aircraft. One skilled in the art will recognize, however, that the disclosure is not so limited. The system can also be used, for example and not limitation, with automobiles, other types of vehicles, and in power distribution networks. The disclosure can be used to improve control and reduce the cost and expense of distributing power in numerous situations by reducing the number of controllers required and eliminating excess controller capacity and reducing, or eliminating circulating current and phase-to-phase imbalances.

The materials and components described hereinafter as making up the various elements of the present disclosure are intended to be illustrative and not restrictive.

Many suitable materials and components that would perform the same or a similar function as the materials and components described herein are intended to be embraced within the scope of the disclosure. Such other materials and components not described herein can include, but are not limited to, materials and components
5 that are developed after the time of the development of the disclosure.

As mentioned above, a problem with conventional power distribution systems is that, generally, each electrical load is provided with an individual controller for power distribution purposes. Unfortunately, this leads to an excess of controller capacity because each individual controller must be rated for the maximum load that
10 the requisite electrical appliance can draw. In addition, in most cases, the controllers are actually designed to provide some margin of safety even though (1) the electrical load itself (e.g., an electric motor) may have some inherent safety margin and (2) many electrical loads are generally used at less than full power and/or are only used intermittently.

To this end, embodiments of the present disclosure relate to a networked system of modular power controllers that can be used individually or in parallel to meet existing power demands. Because every electrical load in an aircraft will rarely, if ever, be on at the same time, the system can be designed with a capacity more
15 closely related to nominal or average power consumption (plus some safety margin) rather than "worst case scenario." As a result, the number of components required, component weight, size, and cost can be reduced, system efficiency can be improved, and improved system redundancy can be provided. In the event of a motor controller failure, for example, the system can be reconfigured to assign the load to a
20 functioning motor controller, improving reliability. In addition, if the loads are such that the system is operating at full capacity, all loads can still be powered, albeit at a
25 reduced capacity in some cases.

As shown in Fig. 1, a building block of the system can comprise a plurality of parallel modular converter modules ("modules") **100** that can be networked together to form a parallel modular converter ("converter"), discussed below. In some
30 embodiments, as shown in Fig. 1, each module **100** can comprise onboard

processing. In this configuration, the module **100** can comprise at least three processors: the Motor Control Digital Signal Processor (“DSP”) **105**, the protection processor **110**, and the logic processor **115**. Alternatively, protection processor **110** may be denoted a protection controller, and logic processor **115** may be denoted a
5 logic controller.

In some embodiments, therefore, the DSP **105** can generate, for example, a high-frequency gate drive pulse width modulation signal (PWM) **120** to activate the gate driver **125**. The gate driver **125** acts essentially as the switching side of the power module **100**, much like an electrical relay. In other words, the output **180** of
10 the module **100** is regulated by the PWM signal **120**. To determine the proper PWM signal **120**, the DSP **105** can utilize signals from various sensors via a signal processor **135** and/or signals via a module communications bus **140**, discussed below.

In some embodiments, the DSP **105** can utilize sensors including, for example
15 and not limitation, temperature sensors **150** and shoot-through sensors **155** to detect potentially damaging conditions. In other embodiments, the DSP **105** can utilize sensors including current sensors (to detect overcurrent conditions), voltage sensors (to detect overvoltage conditions), motor speed and position sensors (to detect over-speed conditions). In addition, many of these sensors (e.g., current, voltage, rotor
20 speed and position sensors can also be used to perform motor control). In some embodiments, the signal processor **135** can condition signals from the sensors and can include an Analog to Digital Converter (ADC) **135a**. In other embodiments, the ADC **135** can be a discrete unit that connects via a communications interface to the processors **105**, **110**, **115**. In still other embodiments, the ADC **135** can be integrated
25 into one or more of the processors **105**, **110**, **115**.

Sensor data can comprise, for example and not limitation, module input and output current and voltage, motor position, DC link DM (differential mode) and CM (common mode), voltage and current, motor speed, and power module temperature. In some embodiments, the DSP **105** pulse width modulation method and output
30 power level can be configured by the logic processor **115**. To enable communication

between module processors **105**, **110**, **115** and controllers external to the module **100**, a module communications bus **140** can be utilized. In some embodiments, to enhance module **100** debugging and verification, for example, load sensor signals and DSP configurations can comprise datasets to be transmitted to a master data
5 logger **310**, as discussed below.

It is preferable, and sometimes required, to synchronize the reference clocks between the modules **100** and the motor control DSP **105** to generate synchronous output waveforms **180**. Failure to synchronize reference clocks can result in the motor control DSP **105** generating waveforms that are out-of-phase from the
10 waveforms of other modules **100**. This, in turn, can potentially create short circuits, which can damage or destroy the modules **100**. Variances in the high-frequency system clock of the DSP **105** are relatively insignificant; however, as a few nanoseconds will have little, or no, effect on the output waveforms. The reference clocks are preferably at least synchronized between parallel modules **100** (e.g.,
15 modules **100** that are currently feeding power to the same load). In some embodiments, for very accurate synchronization, methods known in the art such as, for example, synchronization via fiber optic cables can be used. Fiber optic can be advantageous because it is immune to the EMI noise generated by the power module switching. As discussed below, in some embodiments, all motor control PWM
20 signals **120** can be executed on a central processor, which distributes PWM gate signals **120** directly to the gate drive circuitry **125** of the IGBT switch modules. This can reduce synchronization issues because paralleled modules receive identical gate signals **120**.

In some embodiments, the protection processor **110** can enable safe operation
25 of the module **100**. The protection processor **110** can monitor various sensors for unsafe operating conditions including, but not limited to, output AC current and voltage sensors **145**, gate driver and inverter temperatures **150**, and shoot-through current **155**. In some embodiments, the protection processor **110** can also monitor, for example, motor over-speed, over-voltage (DC link), overcurrent at input or output,
30 over-voltage at input and output, CM (common mode) current, excessive voltage

ripple, unbalanced input/output current, open phase, and computer failure protection (e.g., if the DSP fails, the protection processor **110** can disable the gate driver **125** independently). In still other embodiments, the protection processor **110** can also compare actual PWM configuration to the commanded PWM configuration. If these signals do not match, the gate driver **125** can also be disabled. In some
5 embodiments, the protection processor **110** can be directly connected to the gate driver **125** enabling nearly instantaneous shutdowns of the inverter **160** should a fault be detected.

Module **100** input fault protection can also be provided by the protection
10 processor **110** in communication with a master protection controller **305** over the module communications bus **140**. Should the protection processor **110** detect a fault, for example, the protection processor **110** can instruct the master protection controller **305** to externally disable the module **100**. In some embodiments, module **100** faults can also be recorded by the protection processor **110**. In some embodiments, the
15 fault can be stored in the memory **110a** (e.g., non-volatile memory) of the protection processor **110** and the module **100** can be disabled until it can be repaired or replaced. To aid in debugging, in some embodiments, the protection processor **110** can also log some or all events with the master data logger **310**. In this manner, information regarding module faults, communications, master logic commands and
20 other pertinent information can comprise datasets for logging by the master data logger **310**.

In some embodiments, the logic processor **115** can regulate the DSP **105** by configuring the modulation method and output power. Coordination between logic
25 processors **115** in parallel modules **100** can enable equal load sharing and clock synchronization. As a result, each logic processor **115** can communicate with the master logic controller **320** for instructions on which load it is assigned to power at present.

As shown, the module **100** can accept a high-voltage DC power (HVDC) that has been rectified by an external rectifier unit. In some embodiments, the input
30 current and voltage can be monitored by current and voltage sensors **165**. The DC

waveforms can be filtered by a DC electromagnetic interference (EMI) filter **170**, which can reduce noise on the DC bus and stabilize input current and voltage. The inverter module **160** can then generate AC waveforms, which can be filtered by an output AC EMI filter **175**, for use by the system loads. In some embodiments, additional filters and processors can be used to remove switching transients and smooth the output waveform. In some embodiments, each module **100** can comprise one small input EMI filter **170**, for example, and a larger output EMI filter **175** for each load (connecting EMI filters in series improves filter attenuation).

Current and voltage waveforms can also be monitored by additional sensors after the output AC EMI Filter **175**. In some embodiments, one or more voltage and/or current sensors at the module **100** and one or more voltage and/or current sensors on the load side. This can enable fault detection in the power switching network **325**, discussed below.

As shown in Fig. **2**, in some embodiments, rather than using an external rectifier, a rectifier **205** can be integrated into the module **200**. In this configuration, the module **200** can utilize an AC power input, such as a 3-Phase AC power input. The rectifier **205** can comprise, for example and not limitation, an active front end (comprising solid state switches) or traditional passive rectifiers (e.g., multi-pulse autotransformer rectifier units, transformer rectifier units, or diode rectifiers). This configuration can provide increased reliability because, for example, a rectifier **205** failure affects only one module **200**. In addition, reliability and safety are improved because there is also a decreased circulating current between modules **200** (e.g., as each module **200** can be isolated from other modules **200**). Of course, this approach incurs a slight increase in cost, weight, volume, and complexity of the modules **200** as the result of the additional components **205**, **210**. In some embodiments, additional current and voltage sensors **210** can be used after the rectifier **205** to sense fault conditions.

Figs. **3A-3C** depict an overall system **300** architecture for a converter. The master controller **302** can comprise, for example and not limitation, a master communications controller **315**, a master logic controller **320**, a master protection

controller **305**, a master data logger **310** or master data logging controller, and a power switching network (PSN) **325**. The master communications controller **315** can connect each module, via each module's **100** module communications bus **140**, enabling message exchanges between modules **100**. In addition, messages from the
5 master logic controller **320** can also be routed by the master communications controller **315** to their respective destinations (e.g., to modules **100**, external aircraft systems **350**, etc.).

In some embodiments, to aid debugging, messages processed by the master communications controller **315** can be duplicated and transmitted to the master data
10 logger **310** where they are recorded for concurrent or future analysis. In some embodiments, the master communications controller **315** can facilitate communications between the modules **100** and external aircraft systems **350** (e.g., aircraft systems **350** external to the system **300** requesting power). In some
15 embodiments, the master logic controller **320** can receive requests for loads at a specified power level (e.g., current and/or voltage) from external airplane systems. The master logic controller **320** can then allocate modules **100** to fulfill power requests by selecting and configuring the modules **100** and power switching network **325** accordingly.

To ensure that any fault conditions occurring in the system **300** are detected
20 and interrupted, the master protection controller **305** can monitor the inputs and outputs to each module **100** including, for example and not limitation, the input current and voltage waveforms of the high-voltage DC Bus and the low-voltage DC Bus. In some embodiments, should a fault occur, the master protection controller **305**
25 can signal the corresponding power switch **330** to disconnect the module **100**, record the failure in the master protection controller memory **305a**, and send a message of the failure to the master data logger **310**. The master protection controller **305** can disable the module **100** until it has been, for example, repaired or replaced.

Logging of control messages and sensor readings, on the other hand, can be
30 handled by the master data logger **310**. The master data logger **310** can record the data it receives to a data storage medium **335** via a data logging bus **345**, which can

be in communication via the data storage interface (DSI) **310a**. In some embodiments, such as when high-frequency sensor readings are to be written to the data storage, high-speed high-capacity storage devices can be used. In some embodiments, the reliability of the system **300** can be enhanced using redundant low-voltage DC connections to the master controllers (e.g., the master protection controller **305**, master data logger **310**, master communications controller **315**, and master logic controller **320**) and the module's **100** processors (e.g., the motor control DSP **105**, protection processor **110**, and logic processor **115**).

In this configuration, the modules **100** can be powered through rectifier units (rectifiers) **340** external to the modules **100**. Each rectifier **340** can power N (any number of) modules **100**. Of course, decreasing the number, N, powered by each rectifier **340** can increase reliability, at the expense of increased weight and complexity. As a result, if there are M rectifiers **340**, for example, this would result in a total of N*M modules **100**. As above, the rectifier **340** can be, for example and not limitation, an AFE, passive diode, or multi-pulse autotransformer unit rectifiers.

In some embodiments, as shown in Fig. 4, the output system **400** can include the power switching network **325**. The power switching network **325** can switch the array of module **100** outputs (**415-1** to **415-N**) to their assigned loads through the array of load connectors (**420-1** to **420-K**). Load fault identification and interruption can be provided by the monitoring of current and voltage waveforms by the power switching network protection controller **405**. Should the power switching network protection controller **405** detect fault conditions, it can open some or all power switching network **325** switches **410** connected to the load. In some embodiments, the power switching network protection controller **405** can also record the fault in NVM to aid with either reclosing the switch **410** (e.g., when the fault has been corrected) or permanently disconnecting a switch **410** (e.g., until it is replaced). The power switching network protection controller **405** can also inform the power switching network **325** of the fault. The power switching network **325** can then open all switches connected to the load, thereby providing redundant system protection. In some embodiments, the output of the system **300** can include a final stage of EMI

attenuation, if required. Each load can have one or more dedicated AC Output EMI filters that can filter the combined waveforms from all parallel modules **100**. In some embodiments, the switches **410** can be, for example and not limitation, solid state switches or electromechanical contactors.

5 In some embodiments, as shown in Fig. **5**, rather than multiple module controllers (e.g., the motor control DSP **105**, protection processor **110**, and logic processor **115**), the modules **100** can be primarily controlled by the motor control DSP **105**. In this configuration, transferring the logic processor **115** functions to the master logic controller **320** can reduce the number of processors required by the
10 module **100**. In some embodiments, this can also eliminate, for example, the power distribution negotiation process between each module's logic processor **115**. In this configuration, the motor control DSP **105** can be configured by the master logic controller **320**. Load sensor signals can be transmitted by the master logic controller **320** to the motor control DSP **105**, as required. In addition, system **300** reference
15 clock synchronization to generate synchronous waveforms can still be provided by the motor control DSP **105**.

 In this configuration, the protection processor **110** functions can be integrated into the reference clock synchronization to generate synchronous waveforms. In most cases, processing the relatively small number of additional signals does not add
20 significant burden to the motor control DSP **105**. Should the motor control DSP **105** identify fault conditions, the motor control DSP **105** can disable the module **100** simply by stopping the PWM signal **120**.

 In some embodiments, to reduce the bandwidth requirements of the module communications bus **140**, the modules **100** can also comprise a separate data-
25 logging communications bus **505**. In this manner, the relatively high-bandwidth data-logging communications can be handled by the data-logging communications bus **505**, while the controls communications **510**, which are relatively low-bandwidth, high reliability communications, can remain on the module communications bus **140**. In this manner, the motor control DSP **105** can be connected to both communications
30 buses **505**, **510** enabling both types of communications.

In still other embodiments, as shown in Figs. 6A-6C, the system **600** can comprise a more prominent master logic controllers **320** and master data loggers **310**, enabling the elimination of the master communications controller **315**. In this configuration, the master logic controller **320** can connect to every module's logic communications bus to enable configurations to be transmitted to the modules **100**. Power distribution between parallel modules **100** and communication with external aircraft systems **605** (e.g., aircraft systems external the system **600**, not the aircraft) can be controlled by the master logic controller **320**. The master data logger **310** can connect to each module's data-logging communications bus **505** enabling higher frequency data logging. In some embodiments, additional connections can be made to the master protection controller **305** and/or the master logic controller **320** for data storage, while the master protection controller **305** can operate substantially, as discussed above.

In some embodiments, as shown in Fig. 7, the system **700** can comprise load sensor signal processing that has been relocated from the individual modules **100** to the system **300** output. In this configuration, the power switching network protection controller **405** can monitor load signals ensuring no faults occur (e.g., over-temperature or over-speed conditions). The power switching network protection controller **405** can relay sensor data including, but not limited to, load temperature **705** and load position **710**, to the master logic controller **320** for distribution to the modules **100**.

Fig. 8 depicts an alternative module **800** architecture that eliminates reference synchronization issues (e.g., the synchronization of reference clocks between the modules **100**, discussed above). In some embodiments, this can be achieved by relocating the motor controller DSP **105** to the Master Control **302**. As mentioned above, the motor controller DSP **105** computes PWM states and then transmits them (e.g., via switch state messages over fiber optics) to the module **800**. Fiber optics can be used for intermodule communication, for example, to prevent data corruption on unshielded electrical wires. In this configuration, a fiber optic transceiver **805** can receive the switch state messages.

A decoder **805a** within the fiber optic transceiver **805** can then generate a gate drive signal **810** for the gate driver **815**. The fiber optic transceiver **805** can transmit, receive, encode, and decode signals from electrical domain to optical and vice versa. Fiber optics signals can be advantageous because optical signals are immune to the
5 EMI noise generated by the power switching network. Optical media can be useful, therefore, to transmit information over relatively long distances (e.g., between modules **100**).

The decoder **805a** can be a logic circuit such as, for example and not limitation, a field programmable gate array (FPGA), complex programmable logic
10 device (CPLD), application specific integrated circuit (ASIC), or processor. The protection processor **110** can provide basic protection by monitoring the current and voltage sensors **812,817** for the DC input and the AC output, respectively, the temperature of module devices **820**, and inverter shoot-through **825**, among other things. Should a fault occur, the protection processor **110** can disable the inverter
15 **830** and inform the master protection controller **305** of the fault. In some embodiments, the protection processor **110** can communicate with the master protection controller **305** via the fiber optic transceiver **805**. In other embodiments, the protection processor **110** can communicate with the master protection controller
20 **305** via the module communications bus **140**. In some embodiments, switch state messages and protection messages can be transmitted at different frequencies to enable concurrent communication.

In yet other embodiments, as shown in Figs. **9A-9C**, the motor controller DSPs
105 can be relocated from the module **100** to the master controller **302**. By consolidating motor controller DSPs **105**, clock synchronization is less difficult due to
25 the close proximity of the devices (e.g., most of the time delay element is removed from the synchronization). In some embodiments, the motor controller DSPs **105** can be placed on a modular accessory board to facilitate repairs of the system **900**. The number of motor controller DSPs **105** can be equal to the maximum number of simultaneous loads, K , to be controlled by the system **900**. In this configuration, each
30 motor controller DSP **105** can calculate the PWM state then transmit a switch state

message to the modules **100**, with parallel modules **100** receiving switch state messages from the same motor controller DSPs **105**. In some embodiments, a PWM router **905** can be used to route the switch state messages to parallel modules **100**. Sensor signals such as, for example, load currents and voltages, can be routed to the
5 respective motor controller DSPs **105** by a load sensors router **910**.

In some embodiments, the master logic controller **320** can communicate directly with each motor controller DSPs **105** to configure the necessary control variables (e.g., pulse width and magnitude). In some embodiments, as above, fiber optic transceivers **805** can be used to communicate with the modules **100**. Multiple
10 wavelengths/frequencies can also be used to enable the concurrent transmission and/or reception of switch state messages and module fault messages.

The architecture discussed above can provide high reliability because each module's **100** controllers operate nearly independently. In most cases, interaction with other controllers is limited to the allocation of power distribution between the
15 logic processors **115** of various modules **100** and the distribution of load and power by the master logic controller **320**. In this configuration, for example, a module **100** failure will not affect the operation of other modules **100**. In addition, communication is simplified as the module communications bus **140** provides and interface between
20 the various module processors (e.g. the DSP **105**, the protection processor **110**, and the logic processor **115**) and the master controllers. However this architecture can be somewhat less cost effective and more difficult to implement. Utilization of a dedicated logic controller for minimal tasks, for example, can result in unused processing power increasing module costs. Integration of logic controller functions
25 into other controllers such as the master logic controller **320**, on the other hand, would decrease costs and module complexity. Implementation of synchronized reference clocks can add complexity and cost to the module.

The overall system architecture, including the subsystems discussed in Figs. **1-9C**, is shown in Figs. **10** and **11**, the system **1000** can control a system of parallel modular inverters **1015** to drive multiple and/or different types of AC or DC machines
30 **1010**. The system **1000** can comprise a plurality of parallel modular inverters **1015**

connected in parallel, each of which is able to be configured to receive any of a plurality control algorithms **1022a**, **1022b**, **1022c** embedded in a motor control system **1020** via a reconfigurable control switching network **1025**. Each of the parallel modular inverters **1015** can be configured to drive one or more of the plurality of AC machines **1010** on the load side via a reconfigurable power switching network **1030**.

This configuration enables, for example, the ability to dynamically reconfigure both the control switching network **1025** and power switching network **1030**. In addition, any of the inverters from the plurality inverters **1015** in parallel is accessible to drive any motor of the plurality motors **1010** (or other electrical loads) on the load side and any control algorithm of a plurality of control algorithms **1022** embedded in the system **1000** is accessible to control any of the plurality inverters **1015**. As a result, one or more inverters **1015** can drive one motor **1010**, as necessary to meet load requirements, and/or a plurality of motors **1010** on the load side can be driven at the same time, each of which can be driven with one or more inverters **1015**. In addition, a plurality of motors **1010** on the load side can be driven at the same time with the same control algorithm (e.g., **1020a**) or a different control algorithm (e.g., **1020b**).

As shown in Fig. **10**, the system can comprise a system controller **1035** configured to communicate with a vehicle controller **1040** to, for example, obtain operation commands from the vehicle controller **1040** and provide system **1000** status signals to the vehicle controller **1040**, among other things. In some embodiments, the system controller **1035** can also reconfigure the power switching network **1030** to provide an appropriate number of inverter modules **1015** in parallel to drive a motor **1010** in real time. In other words, when the load from a motor **1010** is increased, the system controller **1035** can signal the power switching network **1030** to place more inverter modules **1015** in parallel. Conversely, of course, when motor load is decreased, the system controller **1035** can signal the power switching network **1030** to disengage one or more inverter modules **1015**. If necessary, the system controller **1035** can then place them in parallel with other inverter modules **1015** to drive other loads **1010**.

In some embodiments, the system controller **1035** can also reconfigure the control switching network **1025** to provide appropriate motor control algorithms **1022** to one or more of inverter modules **1015** driving one or more motor types. The system controller **1035** can provide algorithms related to, for example and not limitation, field oriented control (FOC), direct torque control (DTC), voltage over frequency control (V/F). This can be useful, for example, to efficiently drive specific motor types (e.g., induction motors, synchronous motors, permanent magnet synchronous motors, brushless DC motors, etc.).

In some embodiments, the system controller **1035** can also send, for example and not limitation, motor speed, torque, or power reference values to corresponding motors **1010** (or motor controllers). In some embodiments, the system controller **1035** can be stored and run on an embedded controller. The system controller **1035** can comprise, for example and not limitation a microcontroller processor, FPGA, or ASIC. In some embodiments, the system controller **1035** can use a real time simulator/emulator or can be run in real-time.

In some embodiments, the number of motor controller algorithms **1022** can be determined by the number of different motor loads. If the system **1000** has three different types of motors **1010** to drive, for example, then three motor controller algorithms **1022** can be developed, with each motor control algorithm **1022** specific to the motor load. Of course, if all three motors **1010** perform the same function with the same motor, it is possible that all three loads can be powered using the same algorithm **1022**.

The control switching network **1025** can dynamically configure one or more inverters **1015** each of which can be driven by a specific control algorithm **1022**, or a common control algorithm **1022**, which is routed through control switching network **1025** per commands from the system controller **1035**. In some embodiments, time delay between signals into and out of control switching network **1025** can be minimized to improve motor drive performance.

The control switching network **1025** can be, for example, in a software or hardware implementation. In some embodiments, a software coded control switching network **1025** can be run on, for example and not limitation, an embedded controller, real-time simulator, or computer. In other embodiments, the control switching network **1025** can be implemented using a hardware device such as, for example and not limitation, CPLDs, ASICs, or FPGAs.

In some embodiments, the power switching network **1030** can dynamically configure one or more inverters to drive one or more motors per one or more specific control algorithms from the system controller **1035**. In some embodiments, the power switching network **1030** can act as a short circuit and/or over current protection device. In this case, the power switches **1030a** associated with the short-circuit or over-current load open when a fault is detected.

The power switching network **1030** can be implemented using, for example and not limitation, solid state relays, mechanical relays, transistors, and other controllable power switches. Of course, the inverters **1015** convert DC power to the requested AC power (e.g., at different voltage levels, frequencies, waveforms, etc.) to drive various AC machines (e.g., AC motors **1010**) per the motor algorithm **1022** and system controller **1035**. The inverters can comprise, for example and not limitation, insulated-gate bipolar transistors (IGBTs), metal-oxide-semiconductor field-effect transistors (MOSFETs), and bipolar junction transistors (BJTs).

In still other embodiments, the system **1000** can assign loads based on a load priority factor. In other words, if, for example, the number of loads requested by external aircraft systems **1040** (e.g., external to the system **1000**) is larger than can be provided by the module **100**, the system **1000** can assign loads by a load priority factor, with higher priority loads being powered before lower priority loads. If the aircraft **1040** makes a request for a large load, such as to lower the landing gear, for example, the system **1000** can temporarily reassign some or all of the modules **1015** to power the landing gear motors. When the landing gear is down and locked, in turn, the system **1000** can reassign the modules **1015** to their previous loads (or to now

existing loads). So, for example, the cabin fan can be temporarily deactivated in favor of the landing gear and then restarted when the gear is down.

In some embodiments, such as when there are an excess of low priority loads that collectively exceed the power rating of the system **1000**, the system **1000** may power some or all of the loads at a reduced setting. In this manner, all loads are
 5 powered, but may operate at a lower speed or capacity. So, for example, the aircraft cabin fans, lighting, and entertainment system may request power at the same time in excess of the system **1000** rating. As a result, the system **1000** can, for example, provide full power to the entertainment system, but slightly reduce cabin fan speeds
 10 and lighting intensity to reduce overall power demand.

As shown in Fig. **12**, embodiments of the present disclosure can also comprise a method **1200** for distributing power. In some embodiments, the method **1200** can comprise receiving **1205** a load request from the vehicle (e.g., load requests from the vehicle controller **1040**). The controller can then determine **1210** if the load
 15 requested is above or below the power rating for a single module. If the load request is below the rating for a single module, the controller can assign **1220a** the load to a single module. If, on the other hand, the load is greater than a single module can power, the controller can parallel **1215** the number of modules ("X") together that are required to power the load and then assign **1220b** the load to the X modules. The
 20 controller can then activate **1225** the modules providing the necessary load.

When the vehicle no longer needs the power supply (e.g., the landing gear is down), the vehicle can request **1230** that the load be disconnected and the controller can disconnect **1235** the module, or modules. In some embodiments, the system can also continuously or periodically check **1240** for current system requirements and
 25 reassign modules as required.

Example 1

In one example, each module **100** can have a **10A** rating. With ten modules **100** in a converter **300**, therefore, the converter can provide **100A**. If the aircraft requests a **25A** load to power the hydraulic motors for the landing gear, for example,

the system **300** can determine that the load requires at least three modules **100**, place three modules **100** in parallel, and then assign and activate three modules **100** to the load. If, during the operation of the landing gear, for example, the power requirements change – e.g., the power required to start the motors is greater than the
5 continuous power to run the motors – the system **300** can remove (or add) modules **100** as the load changes.

Similarly, as shown in Fig. **13**, embodiments of the present disclosure can also comprise a method **1300** for distributing power for multiple loads. In some
10 embodiments, the method **1300** can comprise receiving **1305** at least two load requests from the vehicle. The controller can then determine **1310** if the load requests are above or below the power rating for a single module. If the load requests are below the rating for a single module, the controller can assign **1320b** each load to a single module. If, on the other hand, either (or both) load is greater than a single module can power, the controller can parallel **1315a**, **1315c** two or more
15 modules together and then assign **1320a**, **1320c** the loads to the parallel modules, as required. The system can then activate **1325** the modules. In some embodiments, the system can also continuously or periodically check **1340** for current system requirements and reassign **1320** modules as required. When the vehicle no longer needs the power supply for one or both loads, the vehicle can request **1330** that the
20 load be disconnected and the controller can disconnect **1335** the module, or modules for that load.

Example 2

In another example, as above, each module **100** can again have a **10A** rating and ten modules **100** in a converter **300** for a total of **100A** capacity. If the aircraft
25 requests a first, **15A**, load to power the hydraulic motors for the landing gear, for example, and a second, **7.5A**, load to turn the cabin fan on low, the system **300** can determine that the load requires at least three modules **100**. The system **300** can place a first module **100** and a second module **100** in parallel. The system **300** can then assign the first load to the first module **100** and the second module **100** and the
30 second load to a third module **100**.

The system **300** can again continuously or intermittently check to see if the vehicle power requirements have changed **1340**. If, during the operation of the landing gear, for example, the power requirements change – e.g., the power required to start the motors is greater than the continuous power to run the motors – and/or
5 the vehicle requests that the cabin fan be placed on high, the system **300** can decouple **1315c** the first and second modules, pair the second and third modules and assign **1320c** the first load (the landing gear) to the first module **100** and the second load (the cabin fan) to the second and third modules **100** as the load changes.

Having a plurality of modules **100** in parallel enables the modules **100** to power
10 loads that exceed their individual power ratings. Any number of modules **100** could theoretically be ganged together to power any load. In practice, however, the same input signal does not necessarily produce the same output signal in all modules **100**. This can be due to, for example and not limitation, manufacturing tolerances in the modules **100**, varying resistances (impedances) in the wiring and connections of the
15 system **300**, and variances in the input signals. These variances, in turn, cause variances in the outputs of the modules **100**, which results in load imbalances between parallel modules **100**.

If the load imbalance is large enough, system components can be damaged or destroyed. Because current divides between parallel modules **100** in inverse
20 proportion to their impedance, a larger current flows through the module **100** with smaller impedance. As a result, a module **100** with lower impedance (and relatedly, a lower load capacity) can be overloaded, while a higher impedance module **100** would be loaded below its capacity. Similarly, the effect of phase imbalances from the AC source (e.g., one phase has a large amplitude than the other) is that each module
25 **100** shares the total load unequally.

Whether from a phase imbalance, poorly matched impedance, or other causes, for a **30A** load, for example, each of three modules might not see a consistent **10A**, but instead see **15A**, **8A**, and **7A**. The load sees the correct **30A** and thus operates normally (e.g., the load does not “care” how the power is distributed.)
30 The IGBTs in the inverters **1015**, on the other hand, may carry more than their rated

current and this might cause overheating, destruction of the IGBT devices, or erratic tripping of over-current protection, among other things. This can result in failure of the lower impedance module **100**, poor system utilization, maintenance issues, and poor system reliability.

5 To this end, embodiments of the present disclosure can also comprise systems and methods **1400** for balancing loads, controlling phase-to-phase imbalance, and reducing circulating current between parallel modules **100**. Embodiments of the present disclosure can comprise a method **1400** for balancing the output current between paralleled modules, as shown in Fig. **14**.

10 In some embodiments, the method **1400** can comprise receiving a load request from an external aircraft system **1405**. As before, the method **1400** can then comprise calculating the number of parallel modules required to power the request, as shown at **1410**. So, for example, if a **45A** load is requested, and the system uses **10A** modules, the system can determine that a minimum of **5** parallel modules is
15 required. The method **1400** can continue by calculating the theoretical ideal load sharing between the modules, as shown at **1415**. In other words, the load that each module would power if the impedance of each module was perfectly matched. In the example above, if each module were perfectly matched, for example, each would provide **9A** to power the load. As mentioned above, the modules can be activated by
20 the system controller **1035** and an appropriate motor control algorithm **1022**.

The method **1400** can then measure the output current of each of the activated modules, as shown at **1425**, and then determine if the actual output of each module is approximately equal to the ideal load (from **1415**), as shown at **1430**. In some embodiments, this can be done by direct measurement of the output current or
25 voltage for each module. In other embodiments, the system can monitor other types of feedback in the system, such as, for example and not limitation, inverter temperature, circulating current, or phase imbalance at the load. Modules with higher outputs, for example, will have higher operating temperatures than modules with lower outputs.

As discussed above, because the system uses a single algorithm to calculate the control signals (e.g., PWM gate signals) the outputs of paralleled modules are phase synchronized by design. As a result, any significant imbalance at the load can be an indication of a problem somewhere in the system, such as failing motor windings or insulation causing a short-circuit or an IGBT is beginning to fail. Thus, imbalance at the load can be used as an indication of a fault condition.

In some cases, the terminal voltage of the power switches is small and can be difficult to measure, especially in the presence of large amounts of EMI (generated by the fast switching times) and large currents. As a result, current measurements are generally considered a practical means of determining current sharing imbalances between paralleled modules. If an imbalance exists between the modules, the method can continue by modifying the motor control algorithm to balance the outputs of the modules, as shown at **1435**.

If one phase of one module is providing more current than the others it is paralleled with, for example, the pulse width can be slightly reduced to that module and increased on the other modules to balance their outputs. It is also possible to modify the motor control algorithm to compensate for imbalances. In FOC, for example, the method **1400** can take motor measurements and input commands to generate an “average” output command in rotating coordinate system, and a correction can be applied per module. The method **1400** can then generate a different set of PWM signals for each module based on those corrections. In most cases, inputs are all digital including, for example and not limitation, a variable computed in the control algorithm or direct digital logic PWM signals.

This method **1400** can continue while the load is being powered. In some embodiments, the output current can be monitored constantly, for example, or at a predetermined interval (e.g., once per second). In some embodiments, the method **1400** can end when the vehicle controller indicates the load no longer needs to be powered, for example, or when main power to the aircraft is cut (e.g., for overnight storage of the aircraft).

In other embodiments, as shown in Fig. 15, the system 1500 can comprise a load balancer 1505 for balancing the output current for a plurality of modules, or inverters 1015. The load balancer 1505 can receive inputs from the system 1500 including, for example and not limitation, the requested load from the system controller 1035, the input motor control signal 1510 from the motor control system 1020 (via the control switching network 1025) for each inverter 1015, and the output current 1515 for each inverter 1015. So, for example, if each inverter 1015 is receiving the same input 1510, but a first inverter 1015 is providing a lower output current 1515, the load balancer 1505 can modify the input motor control signal 1510 to the first inverter 1015 to obtain a matched output current 1515 to the remaining inverters 1015.

In some embodiments, the load balancer 1505 can comprise many types of feedback controllers. In some embodiments, the load balancer 1505 can comprise, for example and not limitation, a proportional-integral (PI), proportional-integral-derivative (PID) controller, fuzzy logic, or neural net. In other embodiments, the load balancer 1505 can calculate the theoretical "ideal" load for each inverter 1015 (as previously shown at 1415). In some embodiments, the ideal load can assign an equal portion of the load to each inverter 1015. In this manner, the load balancer 1505 can monitor the output current 1515 for each inverter 1015 and adjust the input motor control signal 1510 accordingly. In this configuration, the error for the load balancer 1505 is the difference between the output current 1515 for each inverter 1015 and the ideal output current (e.g., such that each inverter 1015 is providing the same proportion of the total load requested from the vehicle controller 1040). The load balancer 1505 can then minimize the error (e.g., current imbalance) by adjusting the input motor control signal 1510 to each inverter 1015.

While several possible embodiments are disclosed above, embodiments of the present disclosure are not so limited. For instance, while several possible configurations have been disclosed for the parallel module converter components, other suitable configurations and components could be selected without departing from the spirit of the disclosure. The load balancer 1505 is depicted as a separate

controller, for example; however, the load balancer **1505** could also be incorporated into an existing controller (e.g., the system controller **1035**) to decrease the number of separate components in the system. In addition, the location and configuration used for various features of embodiments of the present disclosure such as, for example, the number of modules, the types of electronics used, etc. can be varied according to a particular aircraft or application that requires a slight variation due to, for example, the size or construction of the aircraft, or weight or power constraints. Such changes are intended to be embraced within the scope of this disclosure.

The specific configurations, choice of materials, and the size and shape of various elements can be varied according to particular design specifications or constraints requiring a device, system, or method constructed according to the principles of this disclosure. Such changes are intended to be embraced within the scope of this disclosure. The presently disclosed embodiments, therefore, are considered in all respects to be illustrative and not restrictive. The scope of the disclosure is indicated by the appended claims, rather than the foregoing description, and all changes that come within the meaning and range of equivalents thereof are intended to be embraced therein.

EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A system for powering a plurality of electrical loads, the system comprising:
 - a first parallel modular converter module having a first input and a first output configured to provide a first alternating current (AC) output to a first load of the plurality of electrical loads;
 - a second parallel modular converter module having a second input and a second output configured to provide a second AC output to the first load;
 - a load balancer connected to the first input, the second input, the first output, and the second output, wherein the load balancer is configured to:
 - compare the first output from the first parallel modular converter module with the second output from the second parallel modular converter module, and
 - modify, upon determining an imbalance exists between the first output and the second output, an associated control algorithm for one or both of the first parallel modular converter module and the second parallel modular converter module to thereby equalize the first output and the second output;
 - a controller configured to generate one or more control signals corresponding to one or more selected control algorithms of a plurality of control algorithms, wherein the plurality of control algorithms includes the associated control algorithm; and
 - a control switching network comprising a plurality of switching elements and configured to transmit a first control signal of the one or more control signals to apply the associated control algorithm to the first parallel modular

converter module and to the second parallel modular converter module when coupled with the first load.

2. The system of claim 1, further comprising:

a third parallel modular converter module having a third input and a third output configured to provide a third AC output to the first load,

wherein comparing the first output with the second output comprises comparing respective output currents of the first output, the second output, and the third output,

wherein modifying the associated control algorithm for one or both of the first parallel modular converter module and the second parallel converter module comprises modifying the associated control algorithm for one or more of the first parallel modular converter module, the second parallel modular converter module, and the third parallel modular converter module, and

wherein equalizing the first output and the second output comprises substantially balancing the respective output currents of the first output, the second output, and the third output.

3. The system of claim 1, wherein the load balancer comprises a proportional-integral-derivative (PID) controller.

4. The system of claim 3, wherein the PID controller is configured to:

determine an amount of imbalance based on a difference between respective output currents of the first output and the second output,

wherein modifying the associated control algorithm for one or both of the first parallel modular converter module and the second parallel converter module is performed by the PID controller to reduce the amount of imbalance.

5. A parallel modular converter comprising:

a first parallel modular converter module configured to provide a first alternating current (AC) output and connected to a module communications bus;

a second parallel modular converter module configured to provide a second AC output and connected to the module communications bus;

a master logic controller configured to assign the first parallel modular converter module and the second parallel modular converter module to power a first load;

a master communications controller connected to the module communications bus and configured to route messages between the master logic controller and the first parallel modular converter module and the second parallel modular converter module, whereby a calculated ideal load sharing value is applied to control the first AC output and to control the second AC output;

a load balancer connected to a respective input and a respective output of each of the first parallel modular converter module and the second parallel modular converter module, wherein the load balancer is configured to:

determine, responsive to application of the calculated ideal load sharing value, that an imbalance exists between the first AC output and the second AC output; and

modify, responsive to determining that the imbalance exists, an associated control algorithm for one or both of the first parallel modular converter module and the second parallel converter module to thereby equalize the first AC output and the second AC output;

a motor control system configured to generate one or more control signals according to one or more selected control algorithms of a plurality of control

algorithms, wherein the plurality of control algorithms includes the associated control algorithm; and

a control switching network comprising a plurality of switching elements and configured to transmit a first control signal of the one or more control signals to apply the associated control algorithm to the first parallel modular converter module and to the second parallel modular converter module when coupled with the first load.

6. The parallel modular converter of claim 5, wherein assigning the first parallel modular converter module and the second parallel modular converter module to power a first load comprises placing the first parallel modular converter module and the second parallel modular converter module in parallel using a power switching network.

7. The parallel modular converter of claim 6, further comprising:

a third parallel modular converter module configured to provide a third AC output and connected to the module communications bus,

wherein assigning the first parallel modular converter module and the second parallel modular converter module to power a first load comprises placing the first parallel modular converter module, the second parallel modular converter module, and the third parallel modular converter module in parallel using the power switching network, and assigning the first load to the first parallel modular converter module, the second parallel modular converter module, and the third parallel modular converter module, and

wherein modifying a control algorithm for one or both of the first parallel modular converter module and the second parallel modular converter module comprises modifying the associated control algorithm for one or more of the first parallel modular converter module, the second parallel modular

converter module, and the third parallel modular converter module to thereby equalize the first AC output, the second AC output, and the third AC output.

8. The parallel modular converter of claim 7, wherein equalizing the first AC output, the second AC output, and the third AC output comprises balancing respective output currents of the first parallel modular converter module, the second parallel modular converter module, and the third parallel modular converter module.
9. The parallel modular converter of claim 8, wherein the associated control algorithm comprises a field-oriented control (FOC) algorithm, and wherein balancing respective output currents comprises modifying a pulse width modulation (PWM) signal for one or more of the first parallel modular converter module, the second parallel modular converter module, and the third parallel modular converter module.
10. A method for balancing outputs between a plurality of parallel modular converter modules, the method comprising:

receiving, at a system controller, a request from a vehicle controller to power a first load;

calculating, using a load balancer coupled with the system controller, a first number of parallel modular converter modules sufficient to power the first load;

placing, using a master logic controller coupled with the load balancer, the first number of modules selected from a plurality of parallel modular converter modules, in parallel;

configuring, responsive to a first control signal from the system controller, a control switching network to transmit, from a plurality of received control signals corresponding to a plurality of control algorithms, a second control signal to the selected modules to apply a first control algorithm thereto, the first control algorithm selected from the plurality of control algorithms, the

control switching network comprising a plurality of switching elements and arranged between the system controller and the load balancer;

sensing, using the load balancer, a respective output from each of the selected modules; and

modifying, using the load balancer and upon determining an imbalance exists between the respective outputs of the selected modules, the first control algorithm for one or more individual modules of the selected modules to equalize the outputs of the selected modules.

11. The method of claim **10**, further comprising:

calculating, using the load balancer, an ideal load sharing value to apply to each of the selected modules,

wherein modifying the first control algorithm for one or more individual modules of the selected modules comprises modifying an input signal to one or more of the selected modules such that the output of each of the selected modules is substantially equal to the calculated ideal load sharing value.

12. The method of claim **11**, wherein modifying the input signal operates to synchronize respective output currents for each of the selected modules.

13. The method of claim **12**, wherein the first control algorithm comprises a field-oriented control (FOC) algorithm, and

wherein modifying the input signal comprises modifying a pulse width modulation (PWM) signal of the FOC algorithm to thereby substantially balance the respective output currents.

14. The method of claim **10**, wherein the first control algorithm comprises a voltage over frequency control algorithm.

- 15.** The method of claim **10**, wherein modifying the first control algorithm for one or more individual modules of the selected modules comprises modifying an input signal with a proportional-integral-derivative (PID) controller of the load balancer.
- 16.** The method of claim **15**, wherein an error for the PID controller comprises a difference between output currents of the selected modules, and
- wherein modifying the first control algorithm for one or more of the selected modules comprises the PID controller modifying the input signal to one or more of the selected modules to reduce the error.
- 17.** The method of claim **11**, wherein the load balancer comprises a proportional-integral-derivative (PID) controller,
- wherein an error for the PID controller comprises a difference between output currents of the selected modules and the ideal load sharing value, and
- wherein the PID controller modifies the input signal to one or more of the selected modules to thereby reduce the error.
- 18.** The method of claim **10**, further comprising:
- calculating, upon determining that a power requirement of the first load has changed, a second number of parallel modular converter modules that is sufficient to power the first load, wherein the second number of modules is less than the first number of modules;
- removing, according to the second number of modules, at least one module from the first number of modules placed in parallel; and
- reconfiguring the control switching network such that the second control signal is no longer transmitted to the removed at least one module.

- 19.** The method of claim **18**, further comprising:

reconfiguring the control switching network to transmit a third control signal of the plurality of received control signals to the removed at least one module to apply a second control algorithm thereto, the second control algorithm selected from the plurality of control algorithms to power a second load.

- 5 **20.** The method of claim **10**, wherein determining an imbalance exists between the respective outputs of the selected modules comprises:

determining that a first operating temperature of a first selected module is greater than a second operating temperature of a second selected module.

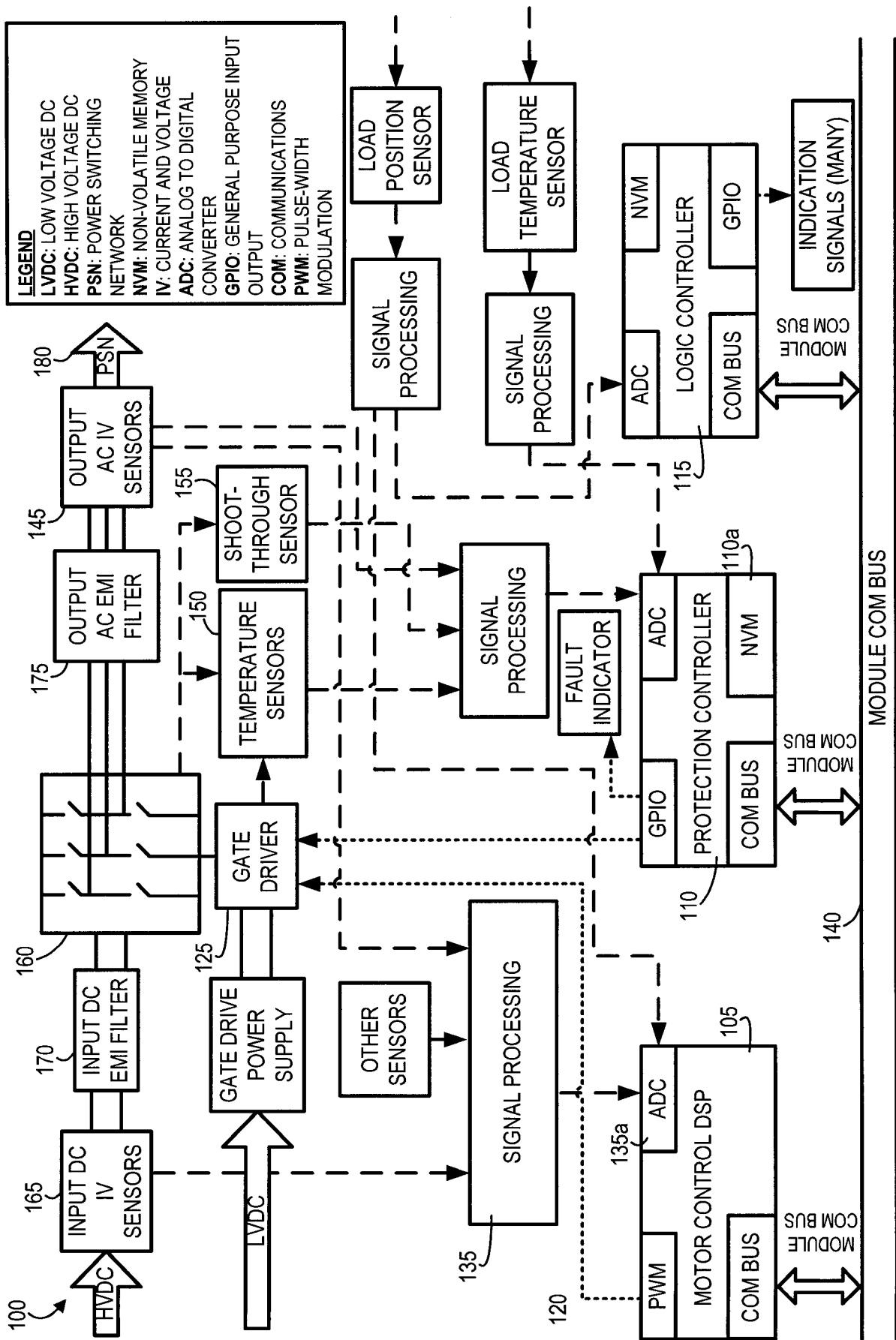


FIG. 1

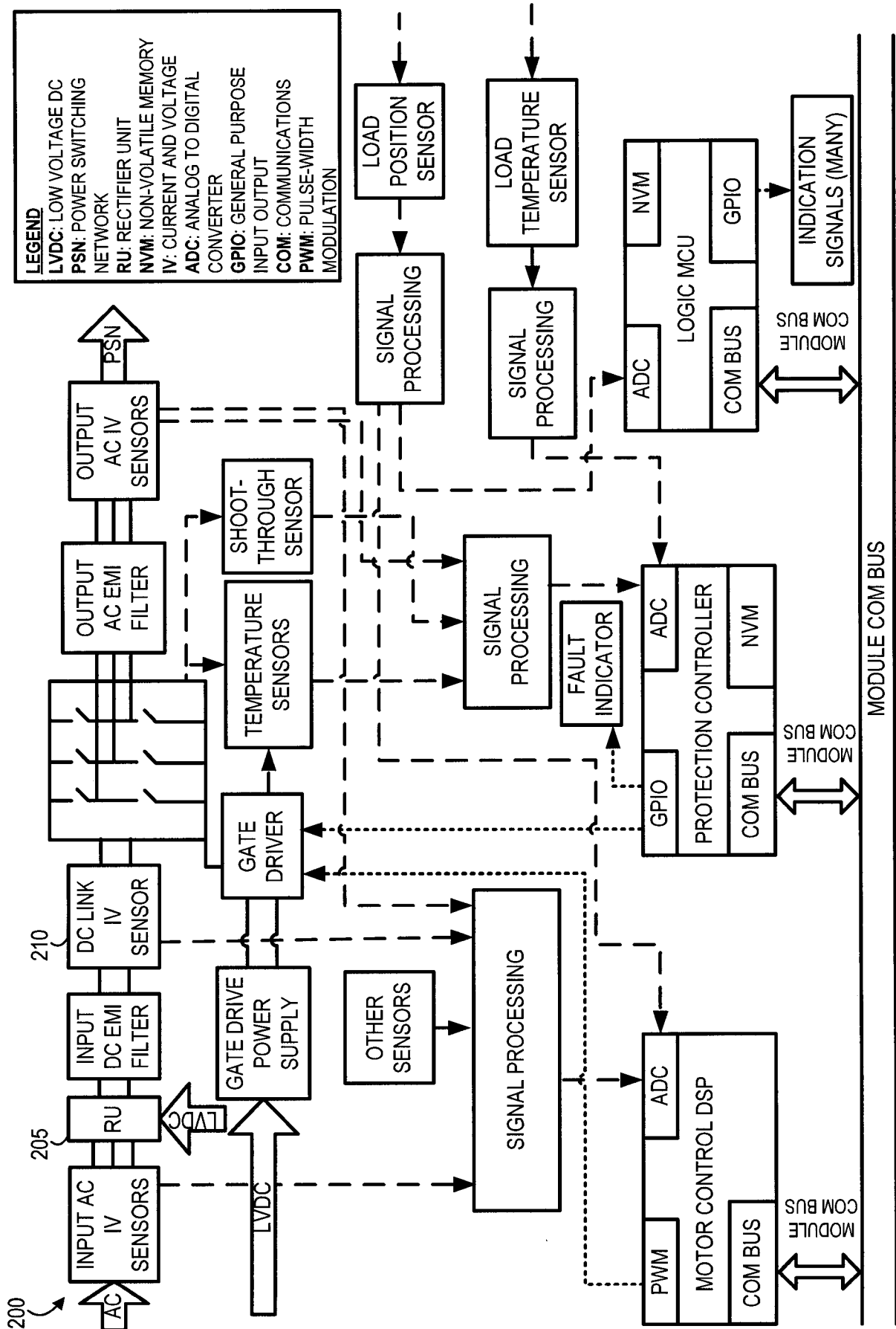


FIG. 2

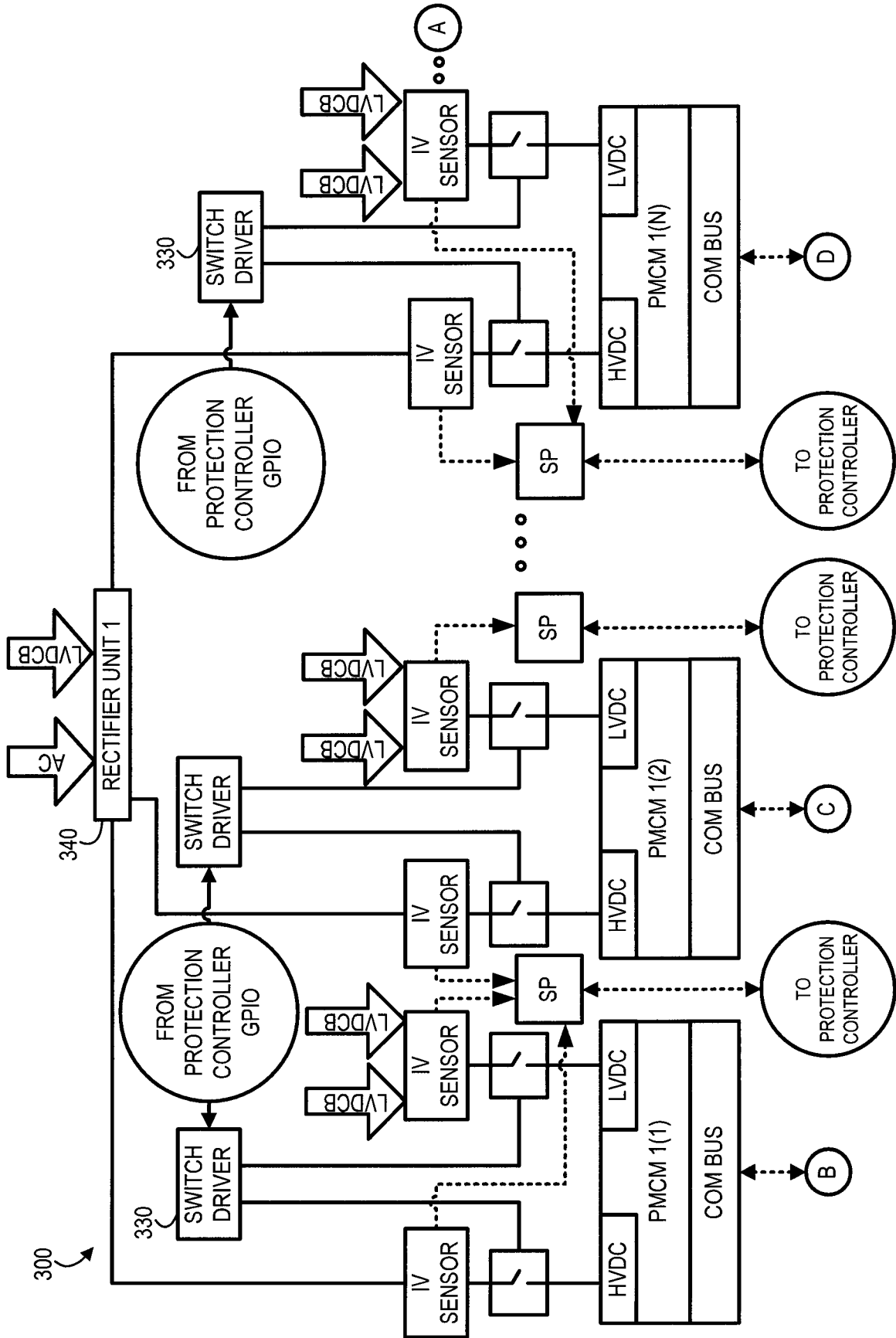


FIG. 3A

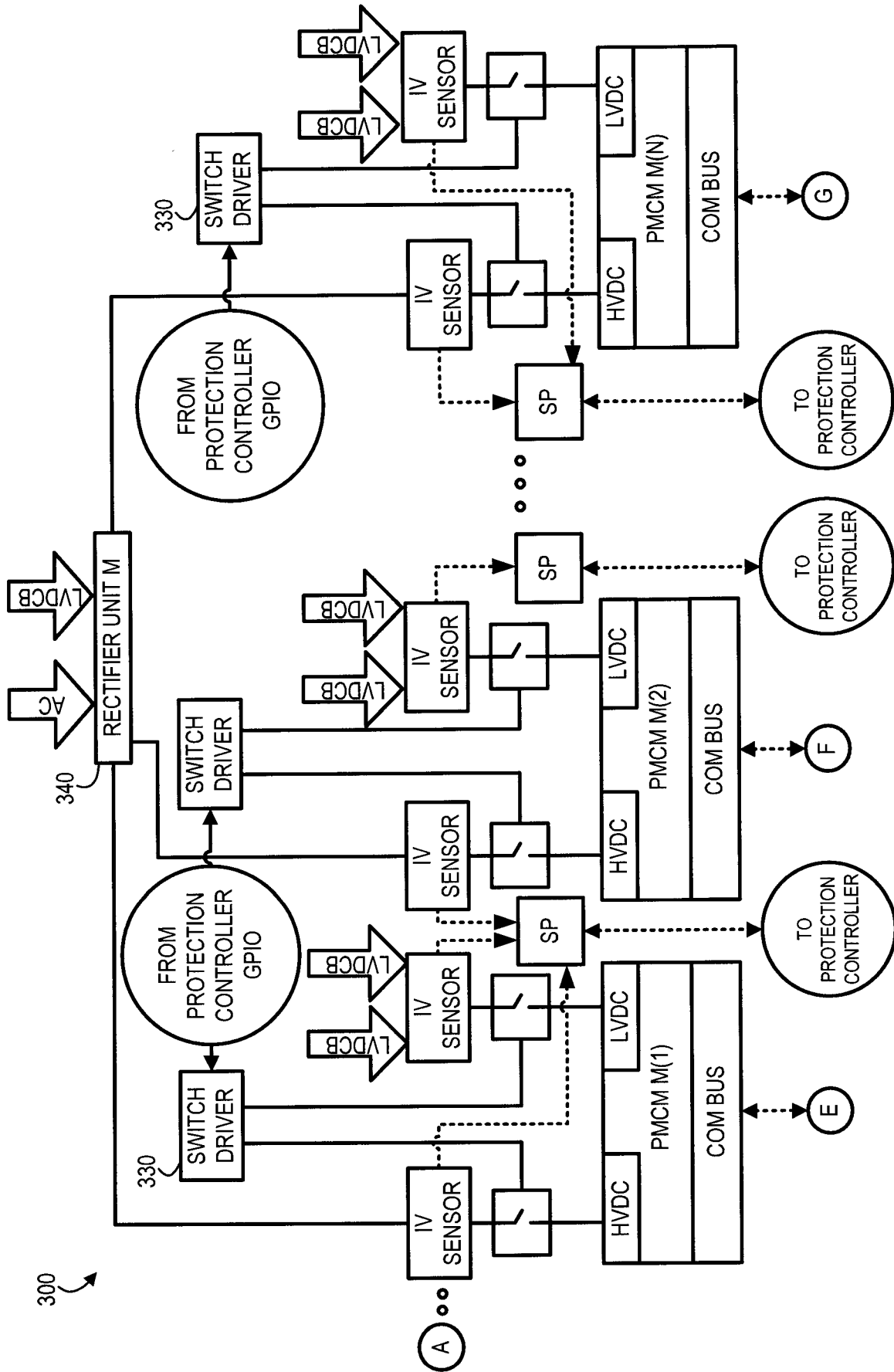


FIG. 3B

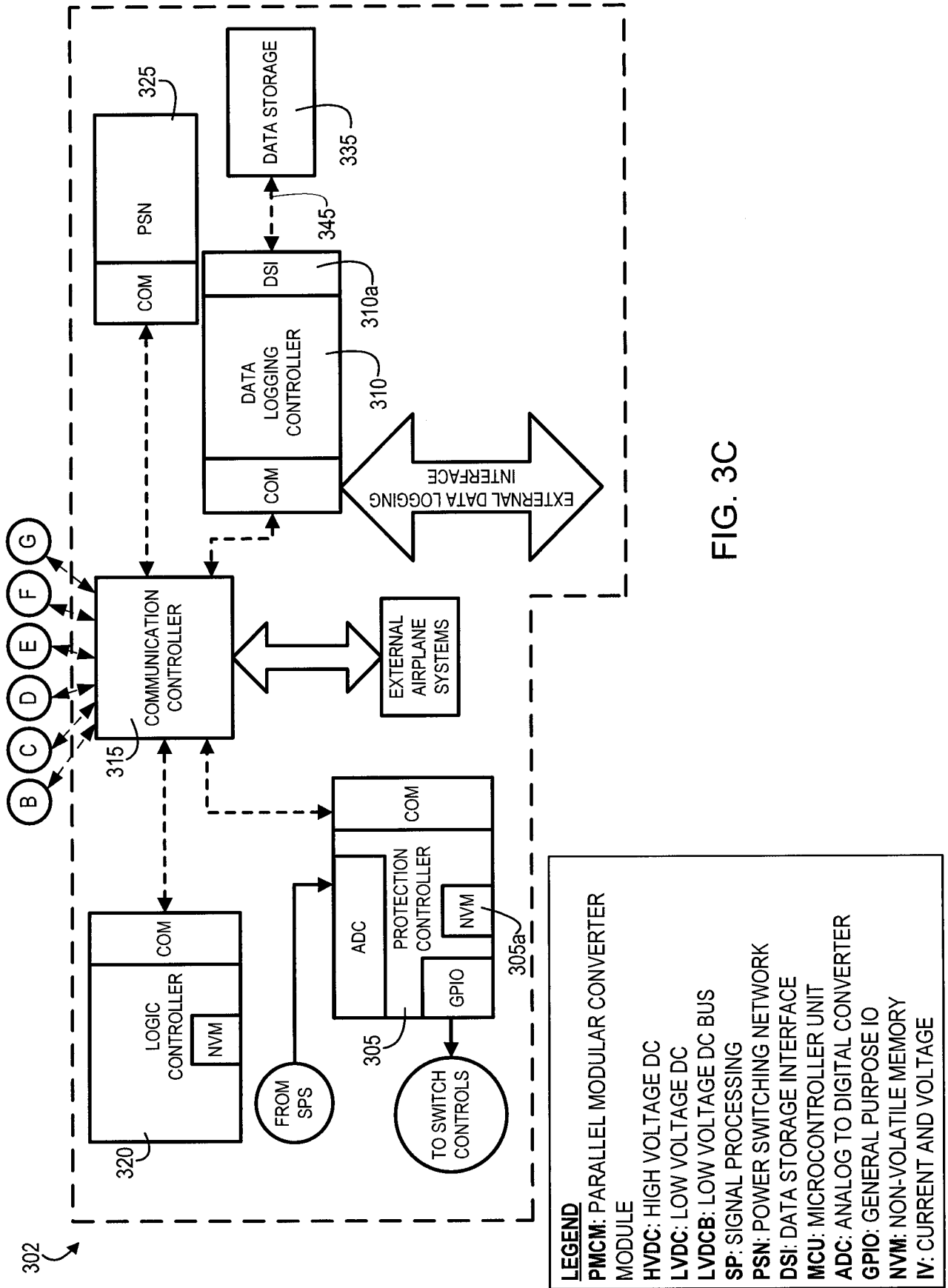


FIG. 3C

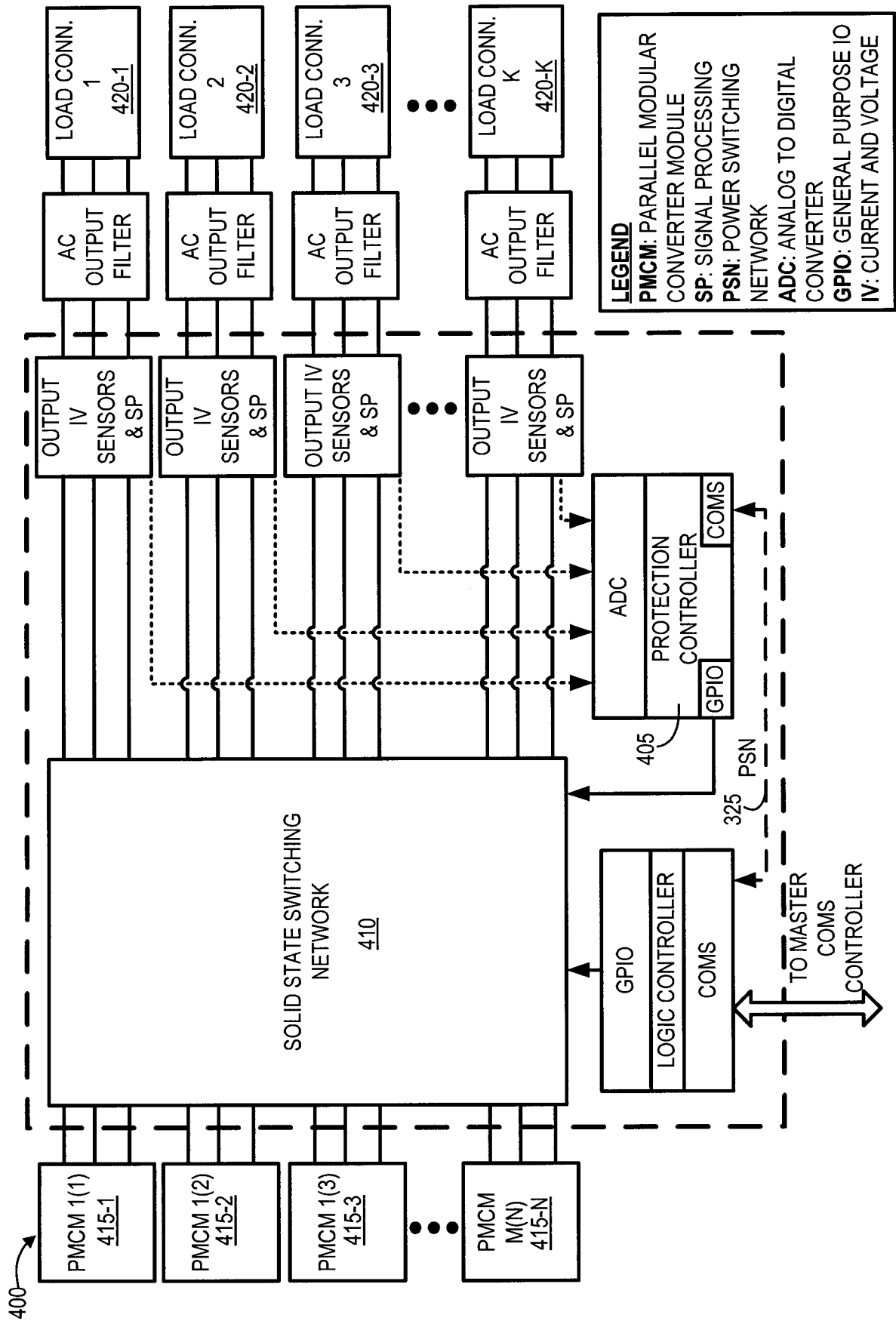


FIG. 4

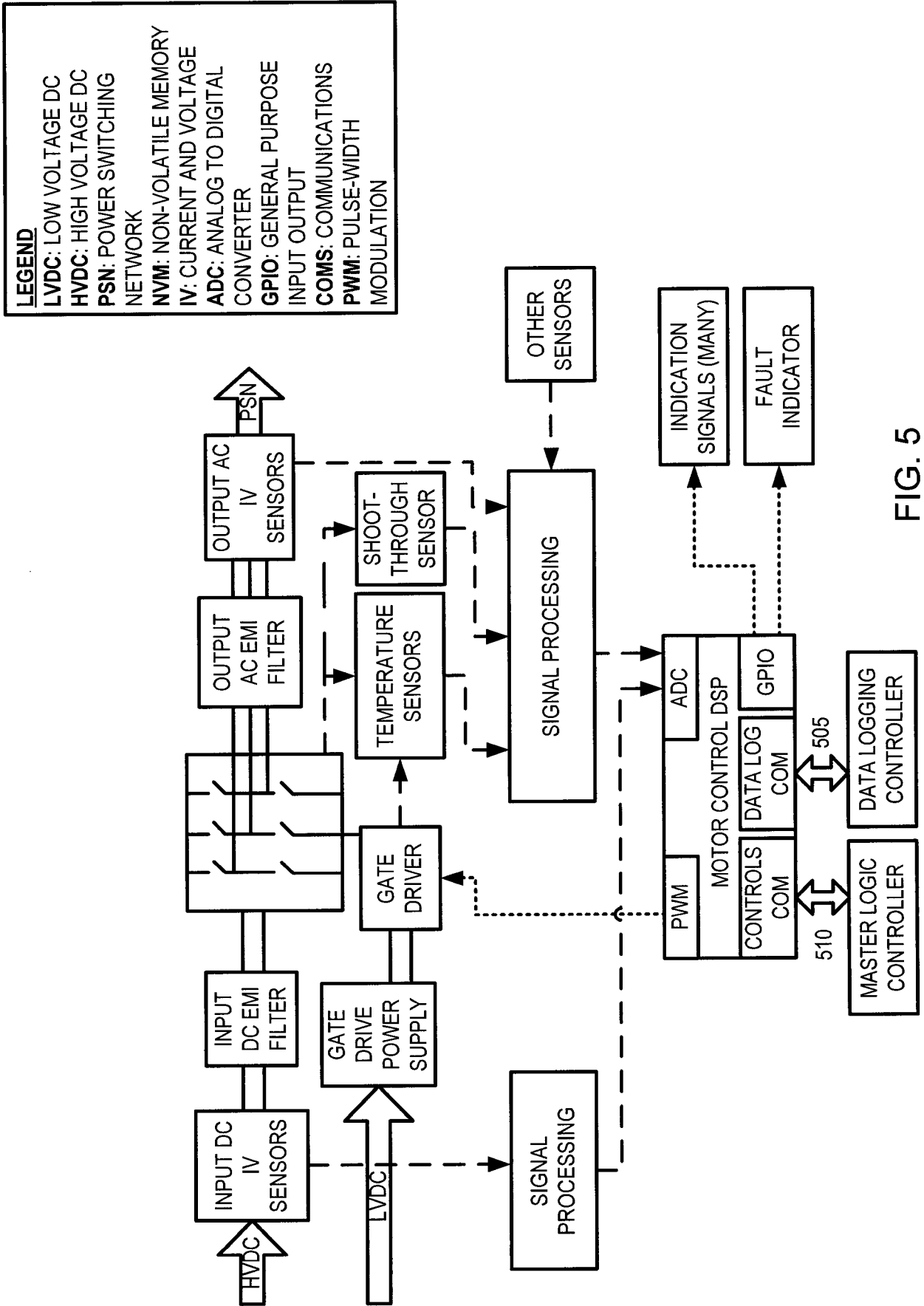


FIG. 5

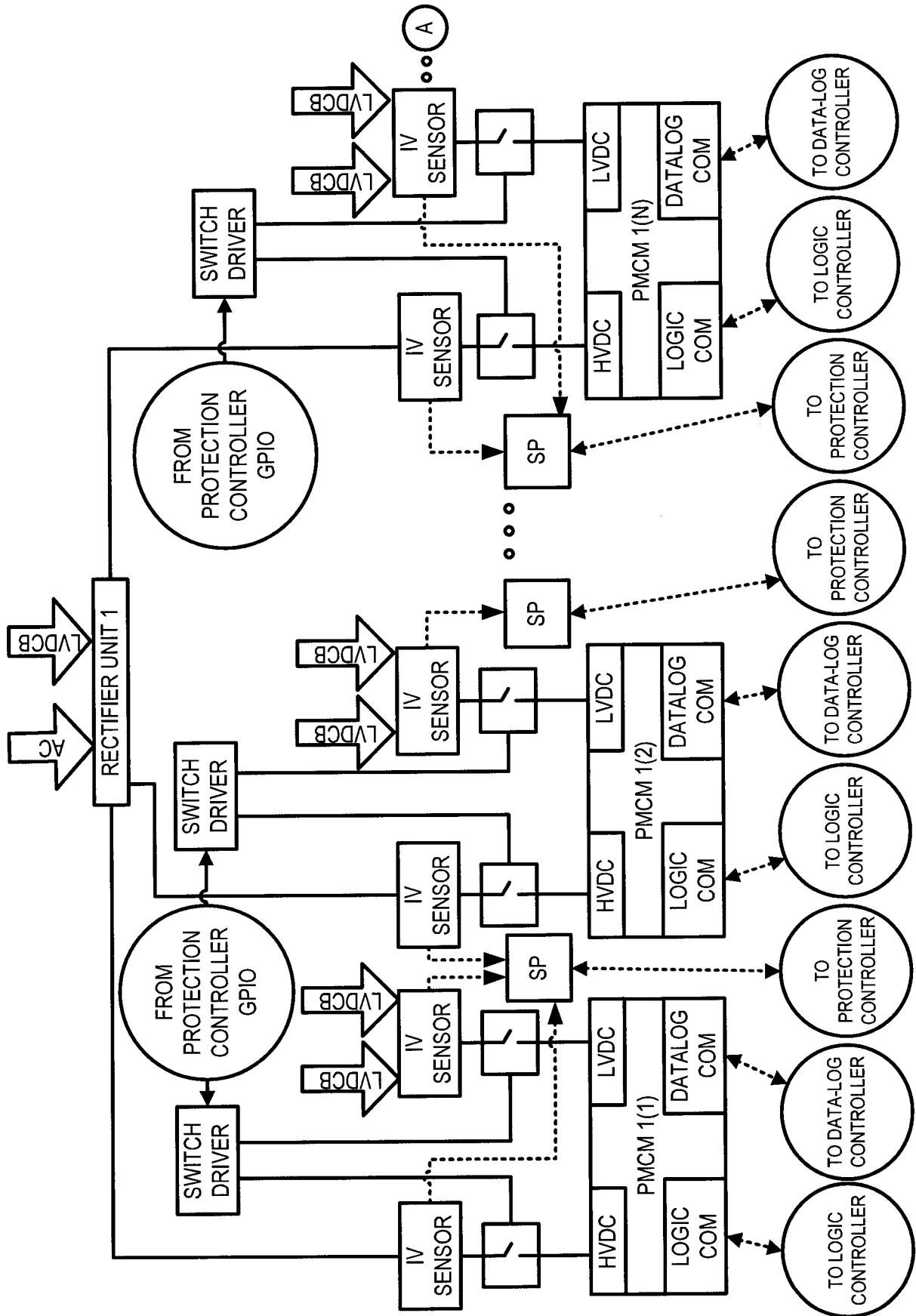
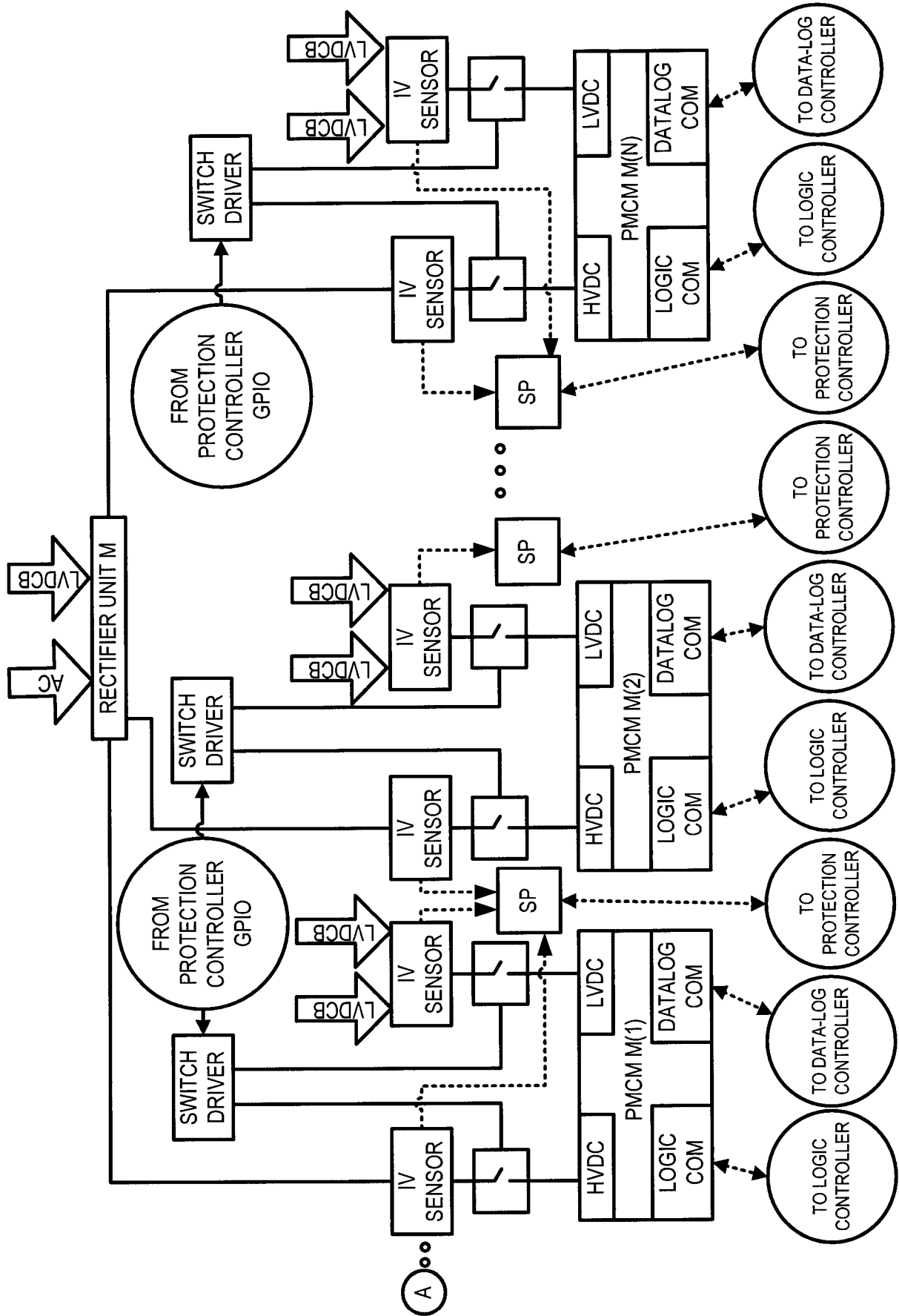
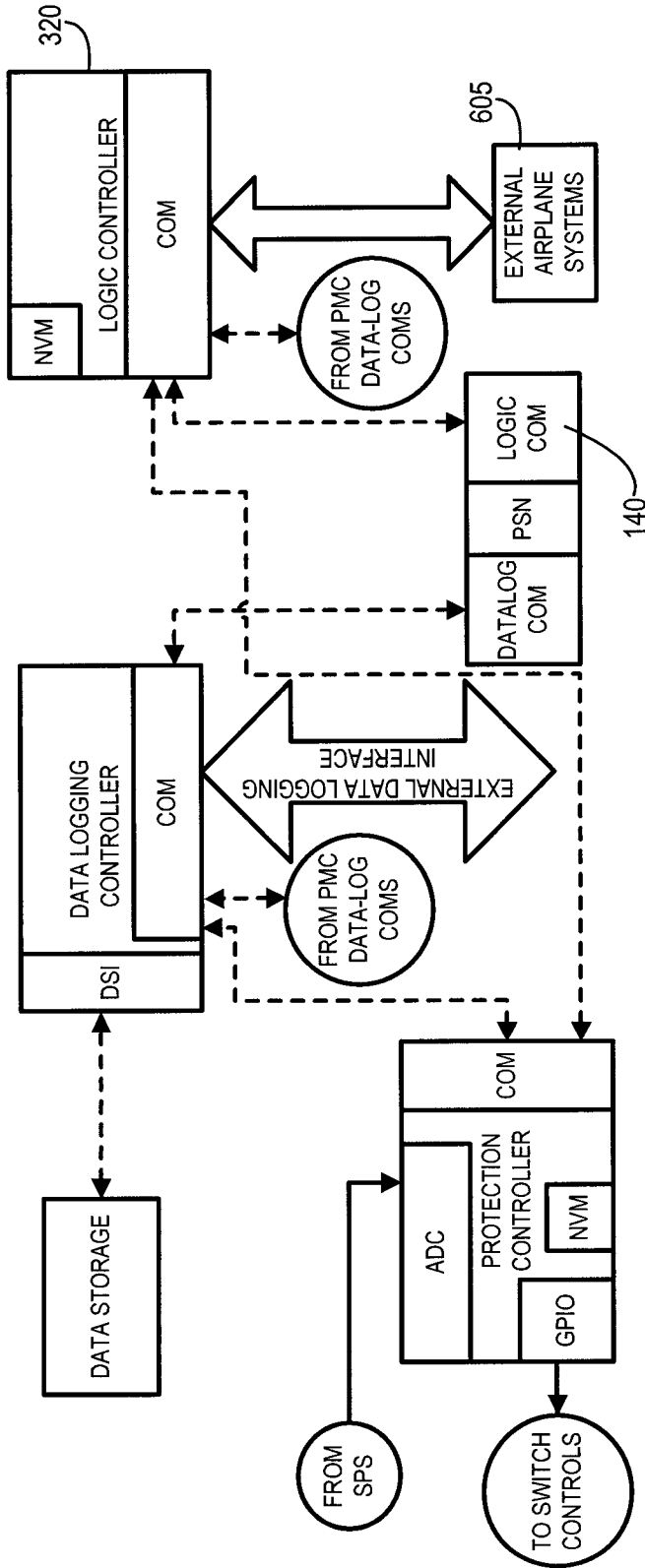


FIG. 6A





LEGEND

- PMCM**: PARALLEL MODULAR CONVERTER MODULE
- HVDC**: HIGH VOLTAGE DC
- LVDC**: LOW VOLTAGE DC
- LVDCB**: LOW VOLTAGE DC BUS
- SP**: SIGNAL PROCESSING
- PSN**: POWER SWITCHING NETWORK
- DSI**: DATA STORAGE INTERFACE
- MCU**: MICROCONTROLLER UNIT
- ADC**: ANALOG TO DIGITAL CONVERTER
- GPIO**: GENERAL PURPOSE IO
- NVM**: NON-VOLATILE MEMORY
- IV**: CURRENT AND VOLTAGE

FIG. 6C

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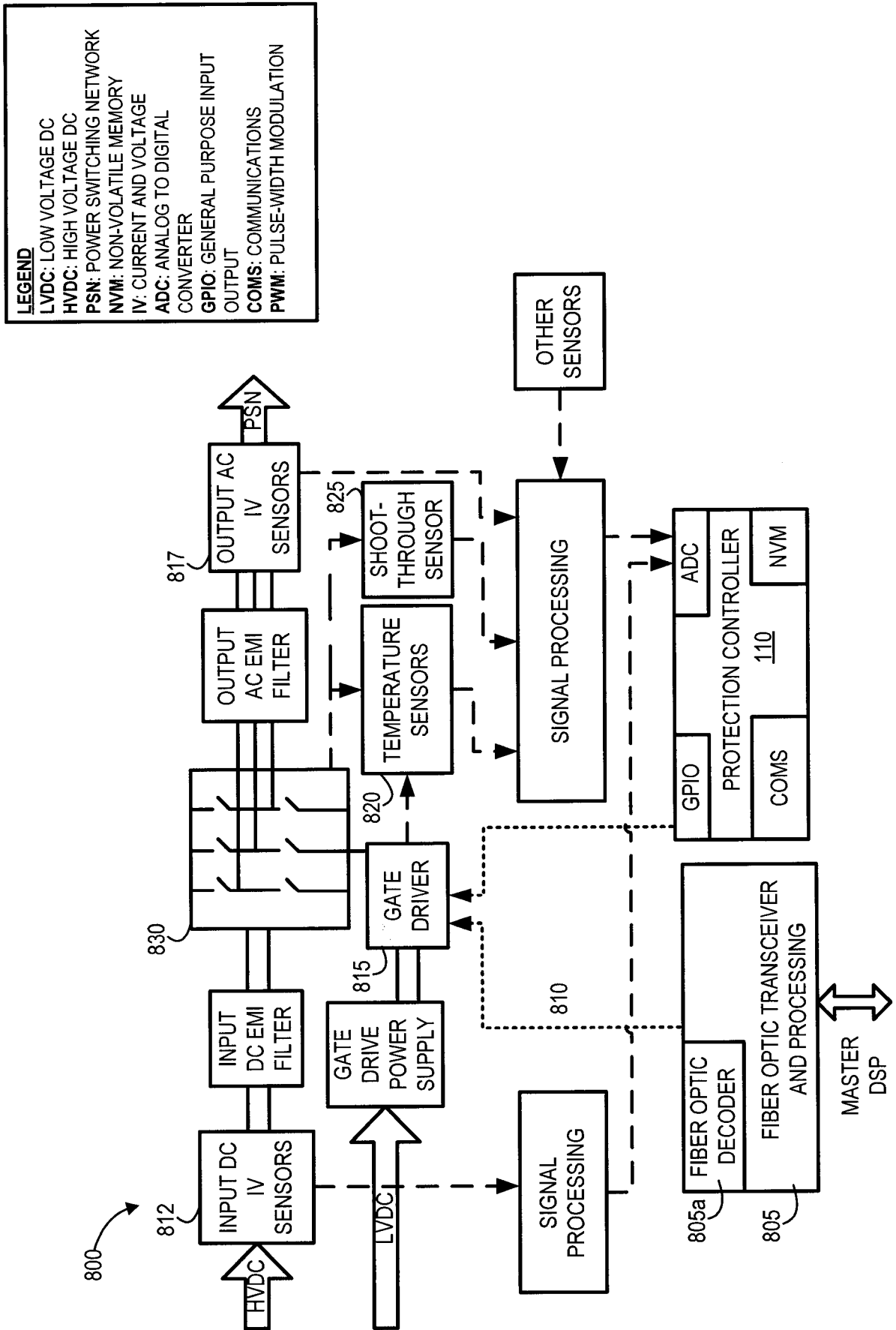


FIG. 8

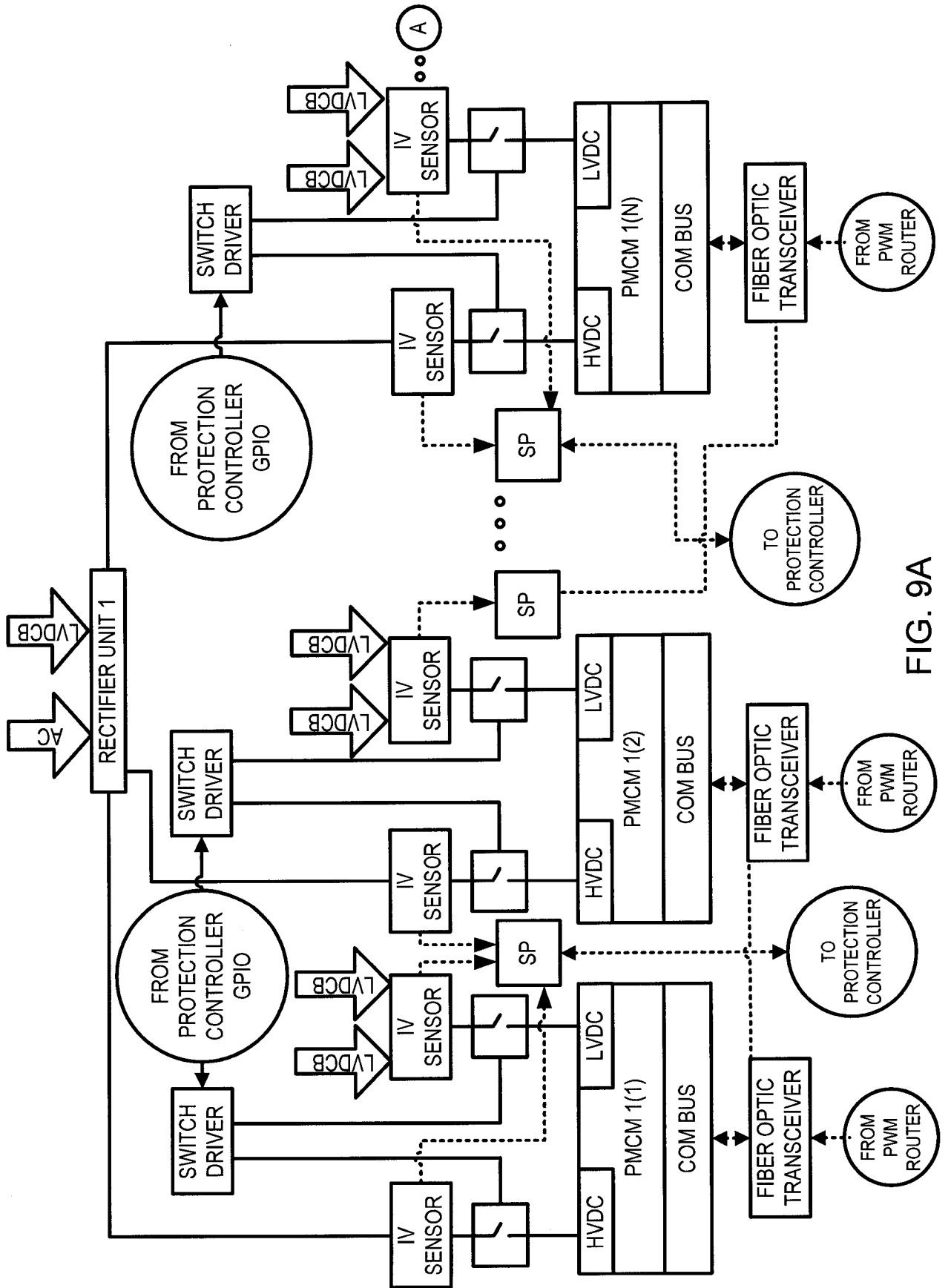


FIG. 9A

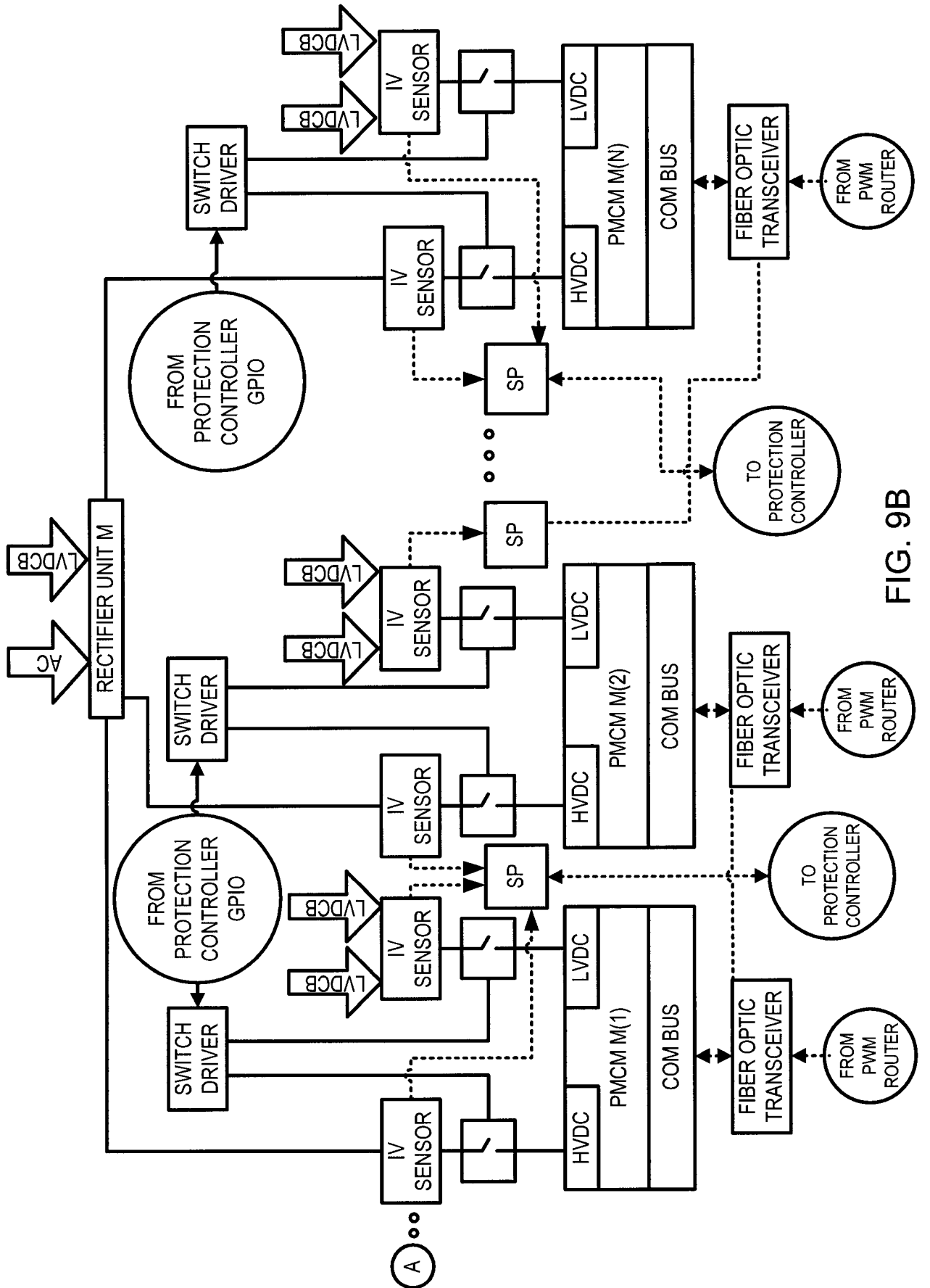


FIG. 9B

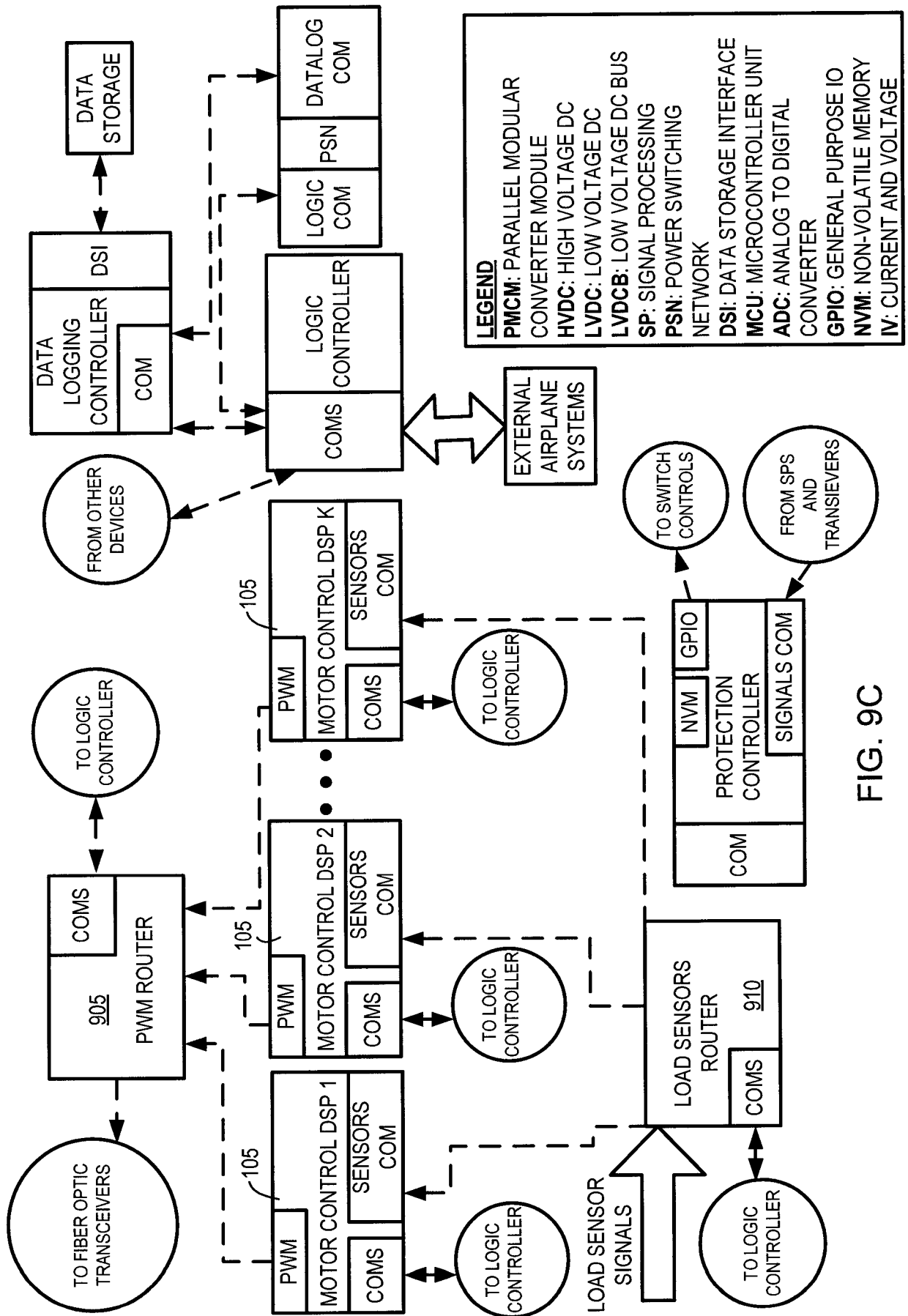
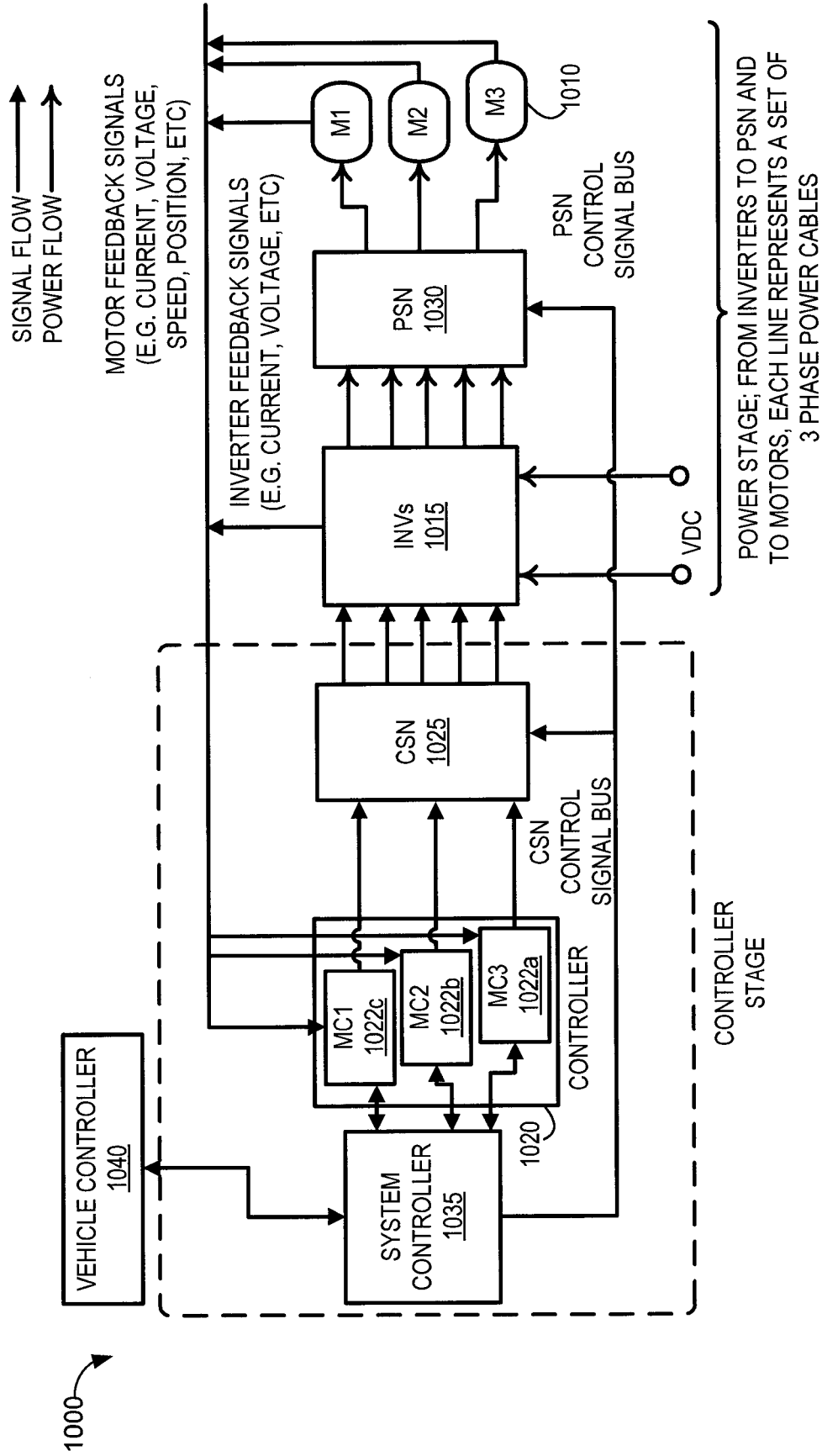
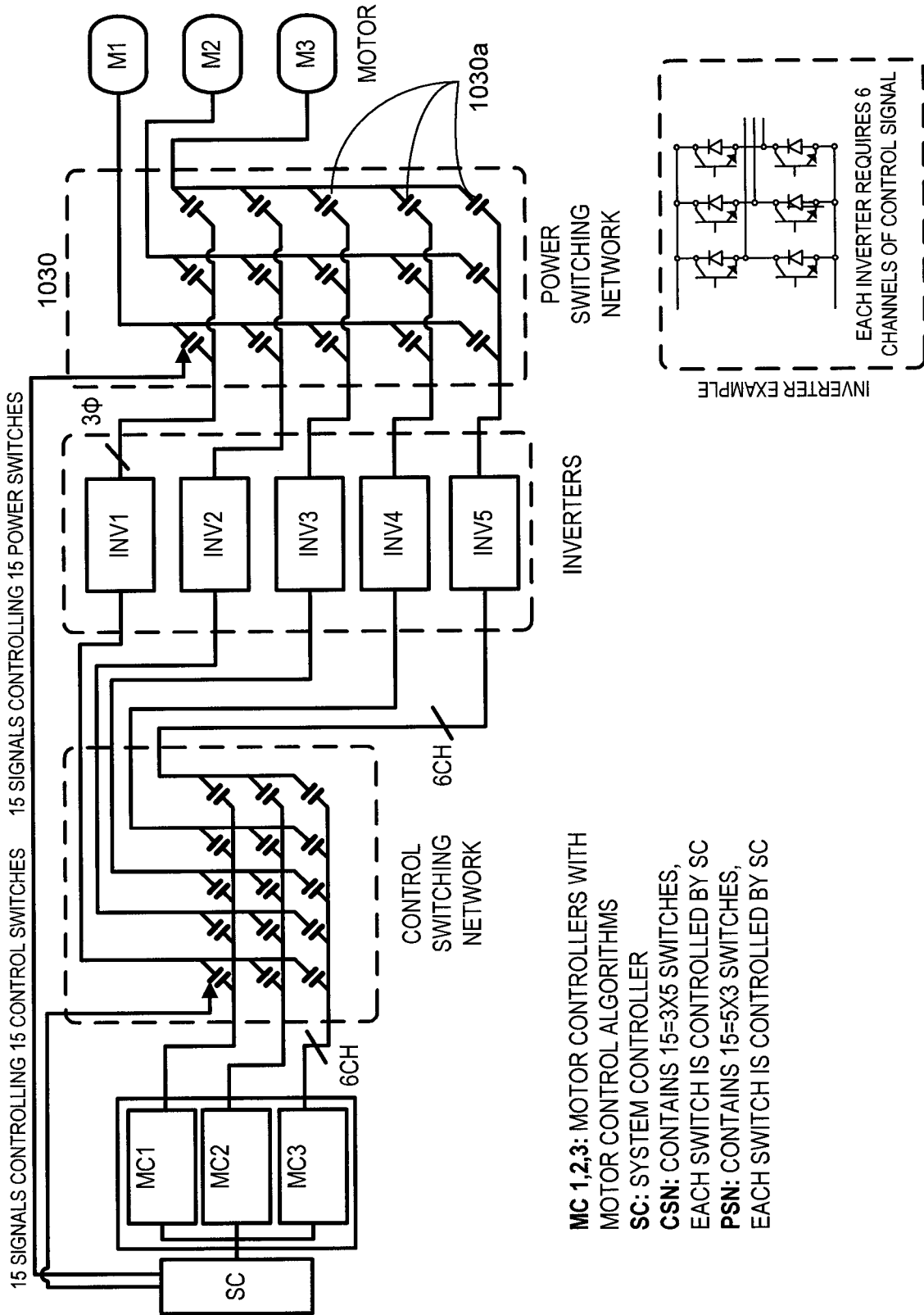


FIG. 9C



MC 1,2,3: REPRESENTS THREE MOTOR CONTROL ALGORITHMS
CSN: CONTROL SWITCHING NETWORK
INVS: INVERTER MODULES
PSN: POWER SWITCHING NETWORK
M1,2,3: REPRESENT THREE MOTORS, CAN BE VARIOUS TYPES

FIG. 10



MC 1,2,3: MOTOR CONTROLLERS WITH MOTOR CONTROL ALGORITHMS
SC: SYSTEM CONTROLLER
CSN: CONTAINS 15=3X5 SWITCHES, EACH SWITCH IS CONTROLLED BY SC
PSN: CONTAINS 15=5X3 SWITCHES, EACH SWITCH IS CONTROLLED BY SC

FIG. 11

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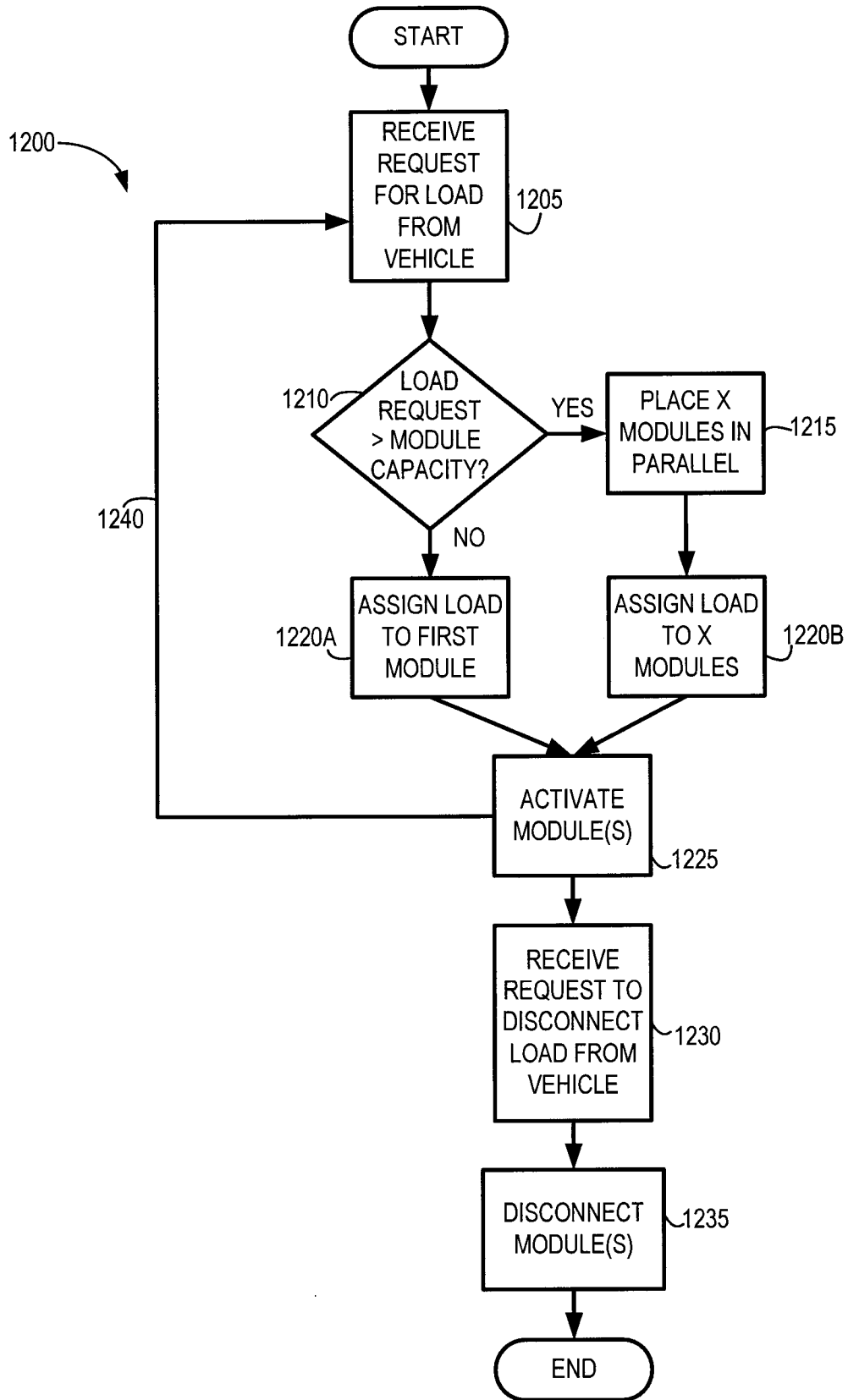


FIG. 12

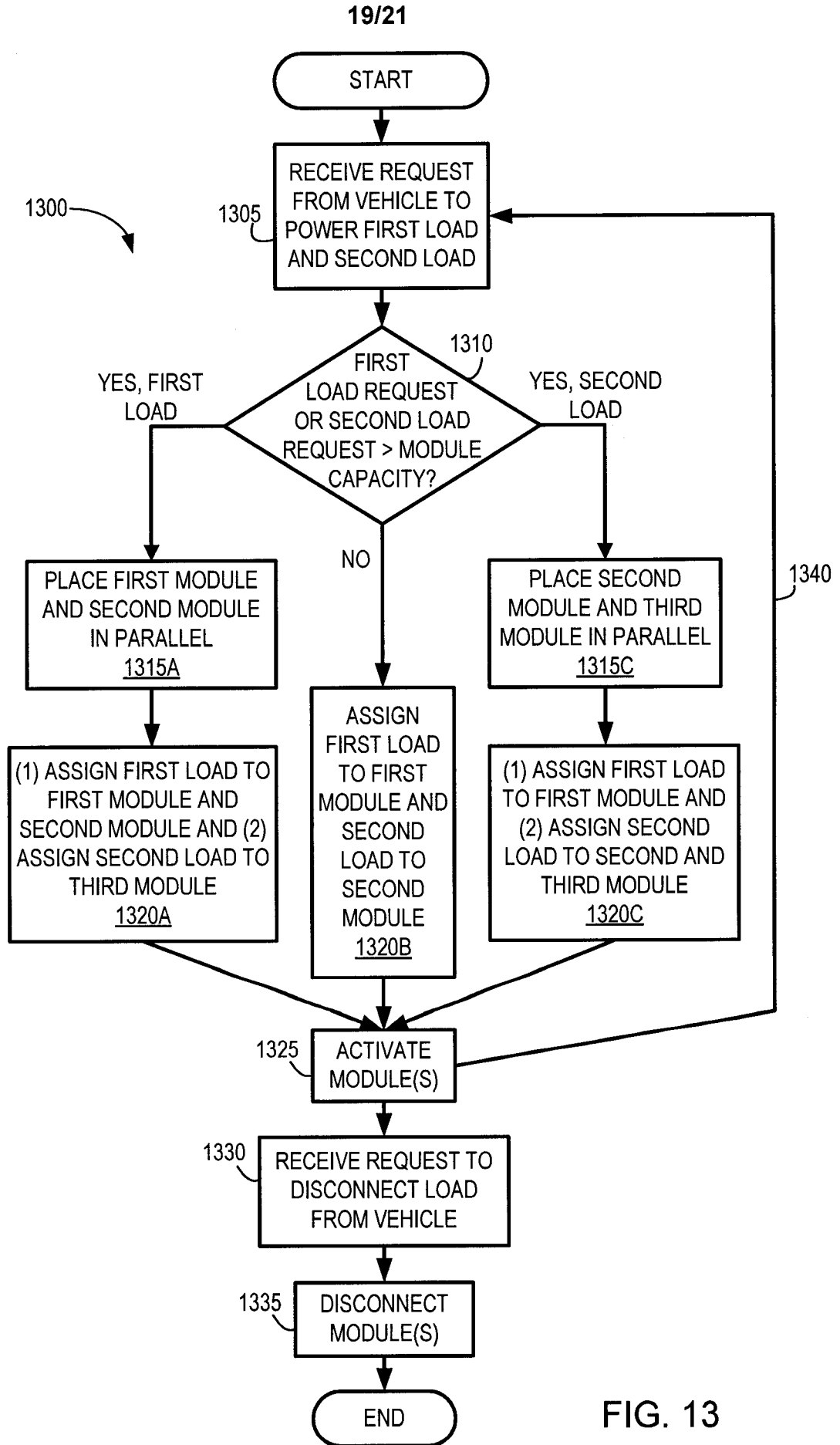


FIG. 13

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FIG. 14

