US008117969B1

(12) United States Patent
Miller et al.

(10) Patent No.: US 8,117,969 B1
(45) Date of Patent: Feb. 21, 2012

(54) **HYDROGEN FUEL CELL HYBRID LOCOMOTIVES**

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(73) Assignee: **BNSF Railway Company**, Fort Worth, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 287 days.

(21) Appl. No.: **12/462,473**

(22) Filed: **Aug. 4, 2009**

Related U.S. Application Data

(60) Provisional application No. 61/137,950, filed on Aug. 5, 2008.

(51) **Int. Cl.**
B61C 3/00 (2006.01)

(52) **U.S. Cl.** **105/50**; 105/26.05; 105/61

(58) **Field of Classification Search** 105/26.05, 105/35, 49, 50, 61; 180/65.1, 65.21, 65.31, 180/68.4, 68.6
See application file for complete search history.

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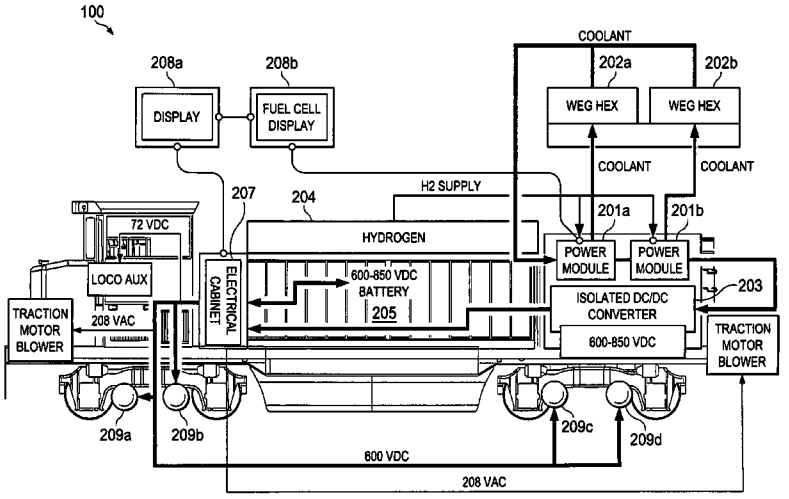
Primary Examiner — S. Joseph Morano
Assistant Examiner — Jason C Smith
(74) *Attorney, Agent, or Firm* — Thompson & Knight LLP; James J. Murphy

(57) **ABSTRACT**

A hydrogen hybrid locomotive including a set of batteries for driving a plurality of electric traction motors for moving the locomotive along a set of railroad rails and a fuel cell power plant for charging the set of batteries and driving the electric traction motors. The fuel cell power plant includes at least one fuel cell power module for generating electrical current by reacting hydrogen fuel and oxygen from intake air, the amount of electrical current being proportional to an air mass flow of the intake air. An air system selectively provides an air mass flow to the fuel cell module to generate an amount of electrical current required for corresponding operating conditions of the locomotive. A cooling system cools the at least one fuel cell power module in response to the amount of current being generated.

22 Claims, 23 Drawing Sheets



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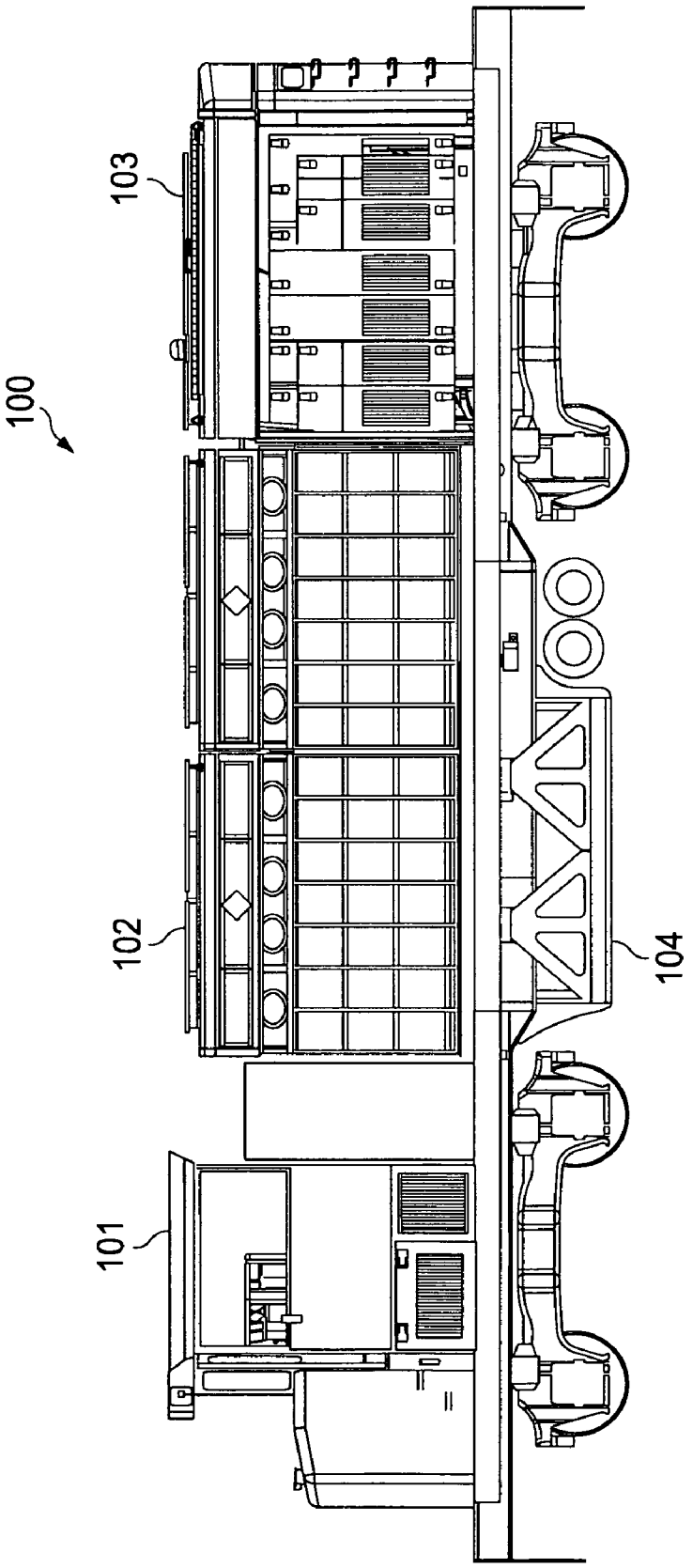


FIG. 1A

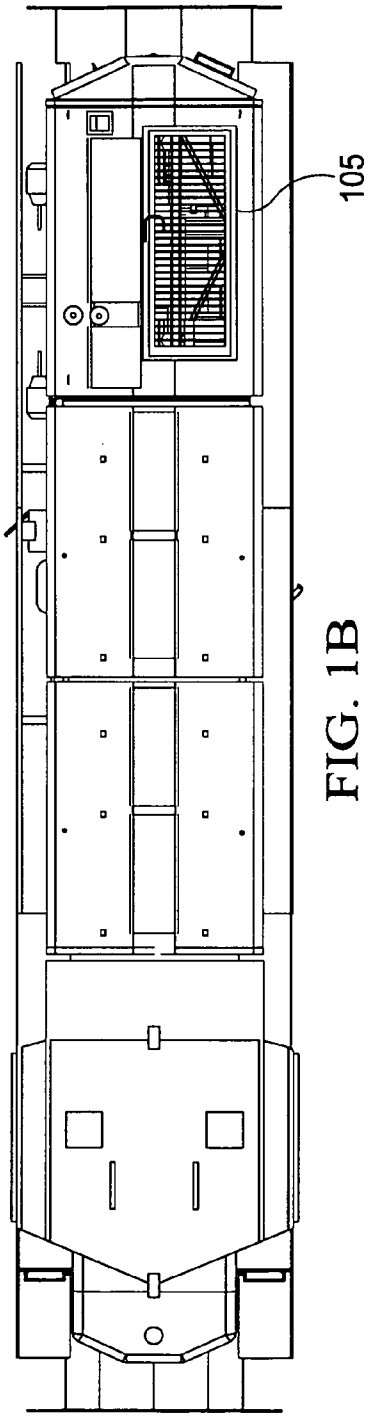


FIG. 1B

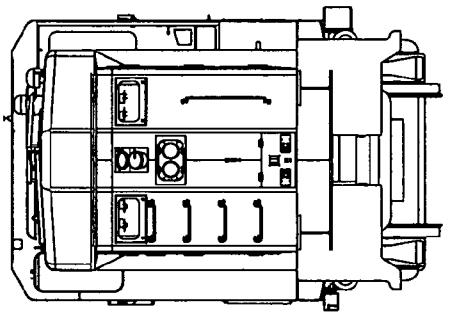


FIG. 1D

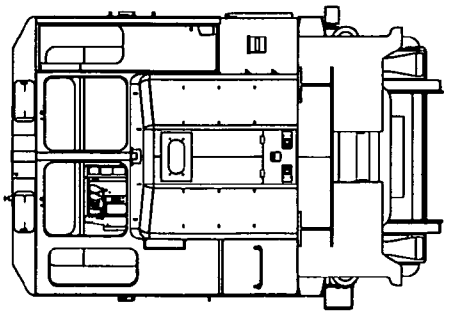


FIG. 1C

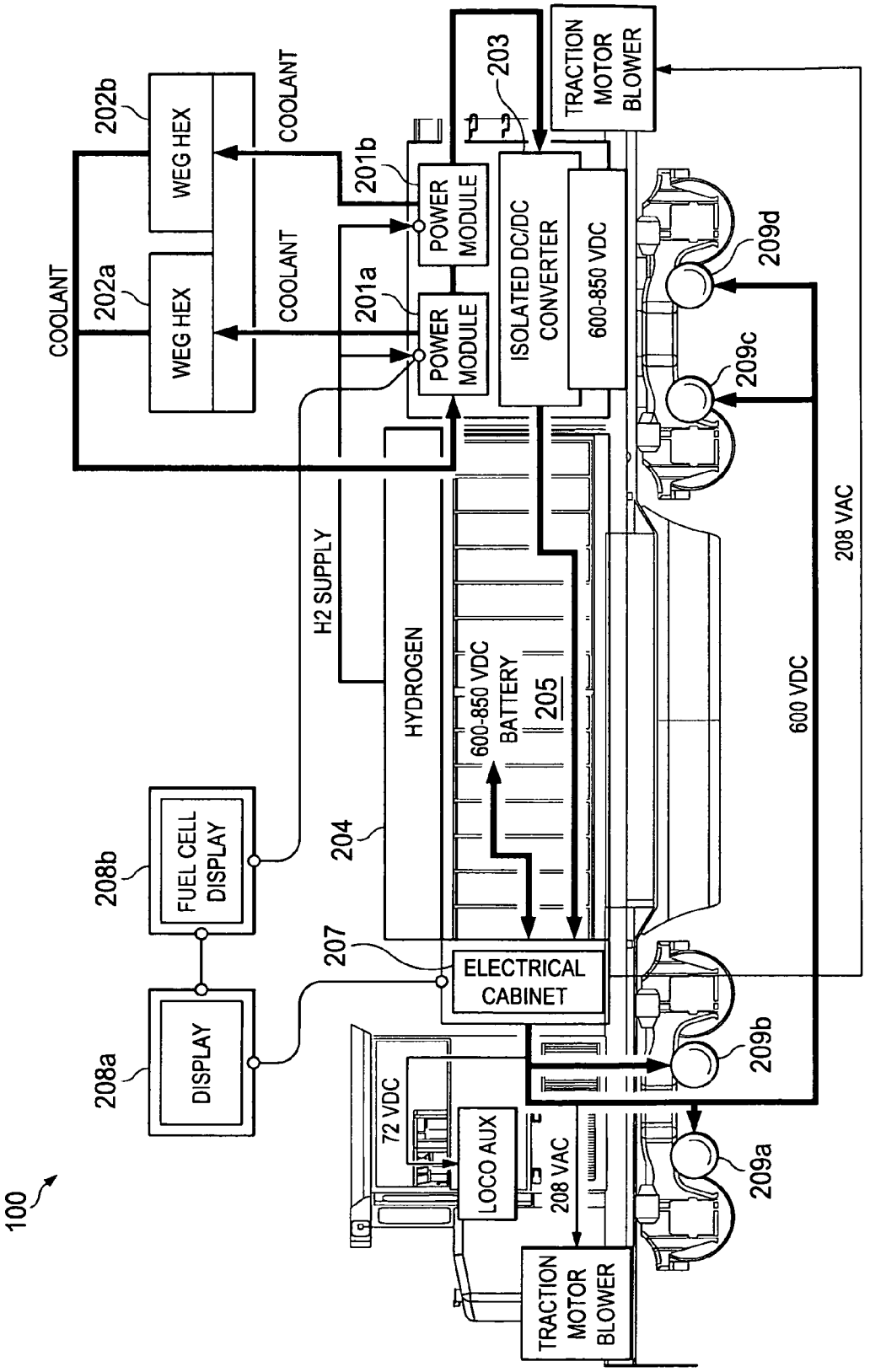

100
COOLANT
202b
WEG HEX
COOLANT
202a
WEG HEX
COOLANT
201b
201a
POWER MODULE
POWER MODULE
203
ISOLATED DC/DC CONVERTER
600-850 VDC
TRACTION MOTOR BLOWER
209d
209c
209b
209a
208 VAC
600 VDC
H2 SUPPLY
HYDROGEN
600-850 VDC BATTERY 205
204
208b
FUEL CELL DISPLAY
208a
DISPLAY
207
ELECTRICAL CABINET
72 VDC
LOCO AUX
208 VAC
TRACTION MOTOR BLOWER

FIG. 2

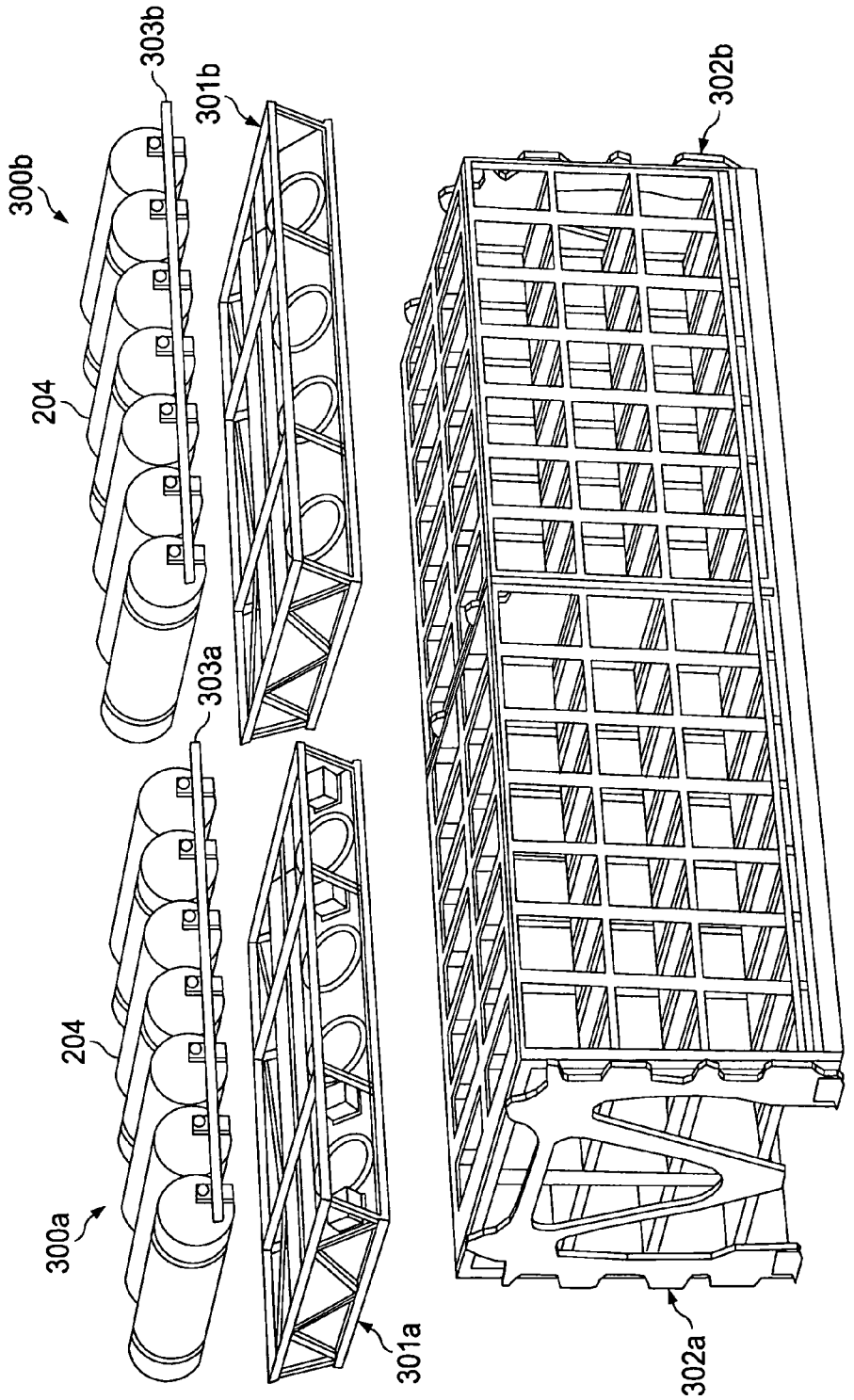


FIG. 3

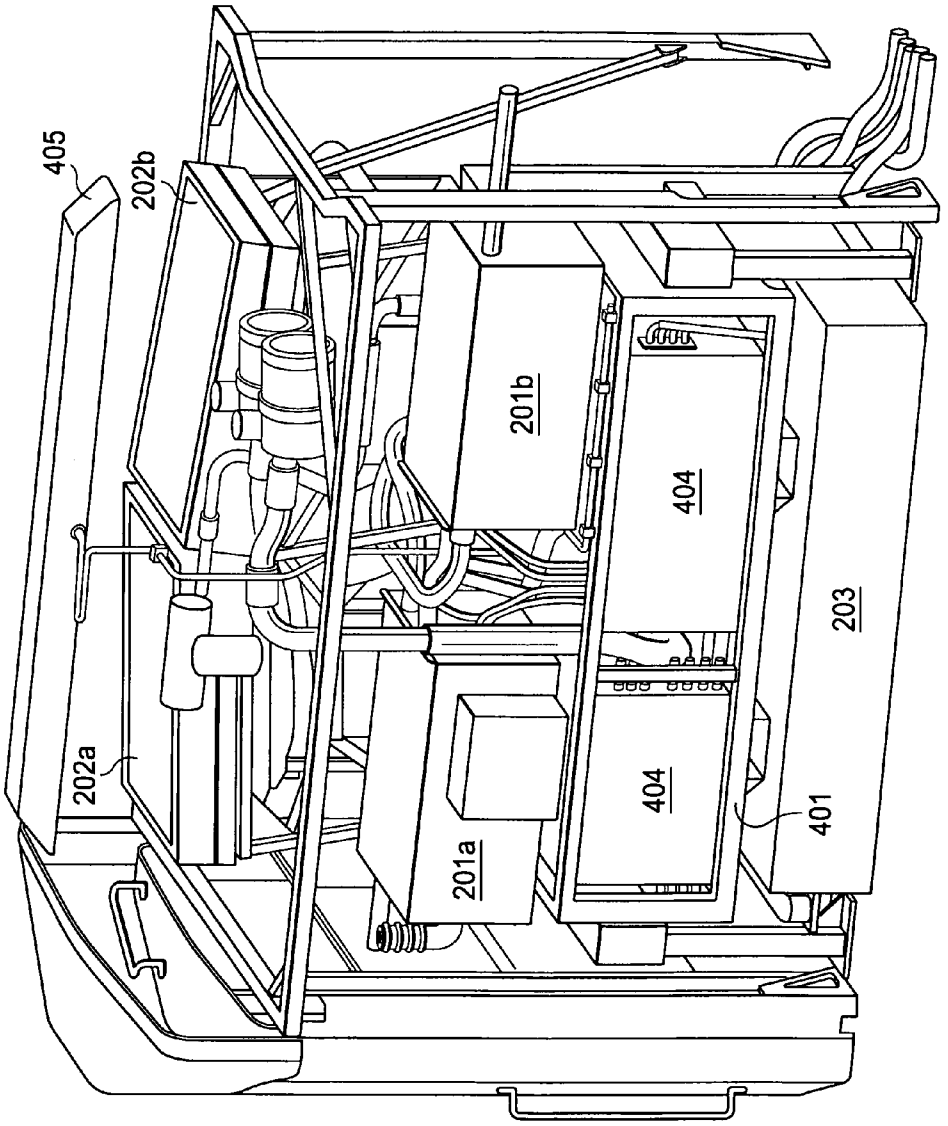


FIG. 4

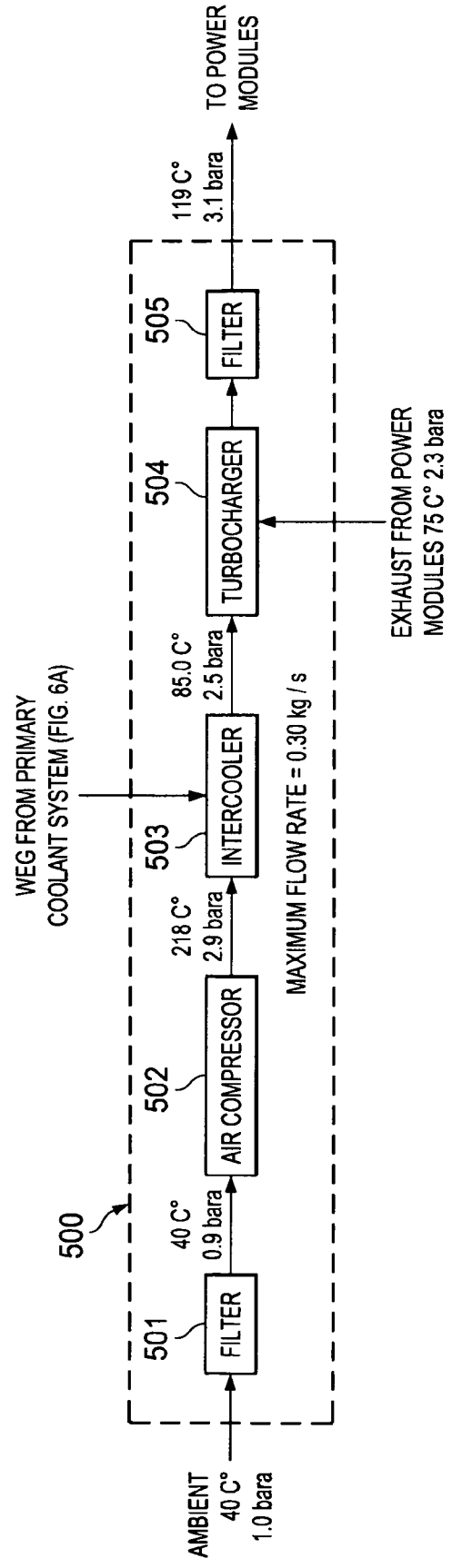

AMBIENT
40 C°
1.0 bara
500
501
FILTER
40 C°
0.9 bara
502
AIR COMPRESSOR
218 C°
2.9 bara
503
INTERCOOLER
85.0 C°
2.5 bara
504
TURBOCHARGER
505
FILTER
119 C°
3.1 bara
TO POWER MODULES
WEG FROM PRIMARY COOLANT SYSTEM (FIG. 6A)
EXHAUST FROM POWER MODULES 75 C° 2.3 bara
MAXIMUM FLOW RATE = 0.30 kg / s

FIG. 5A

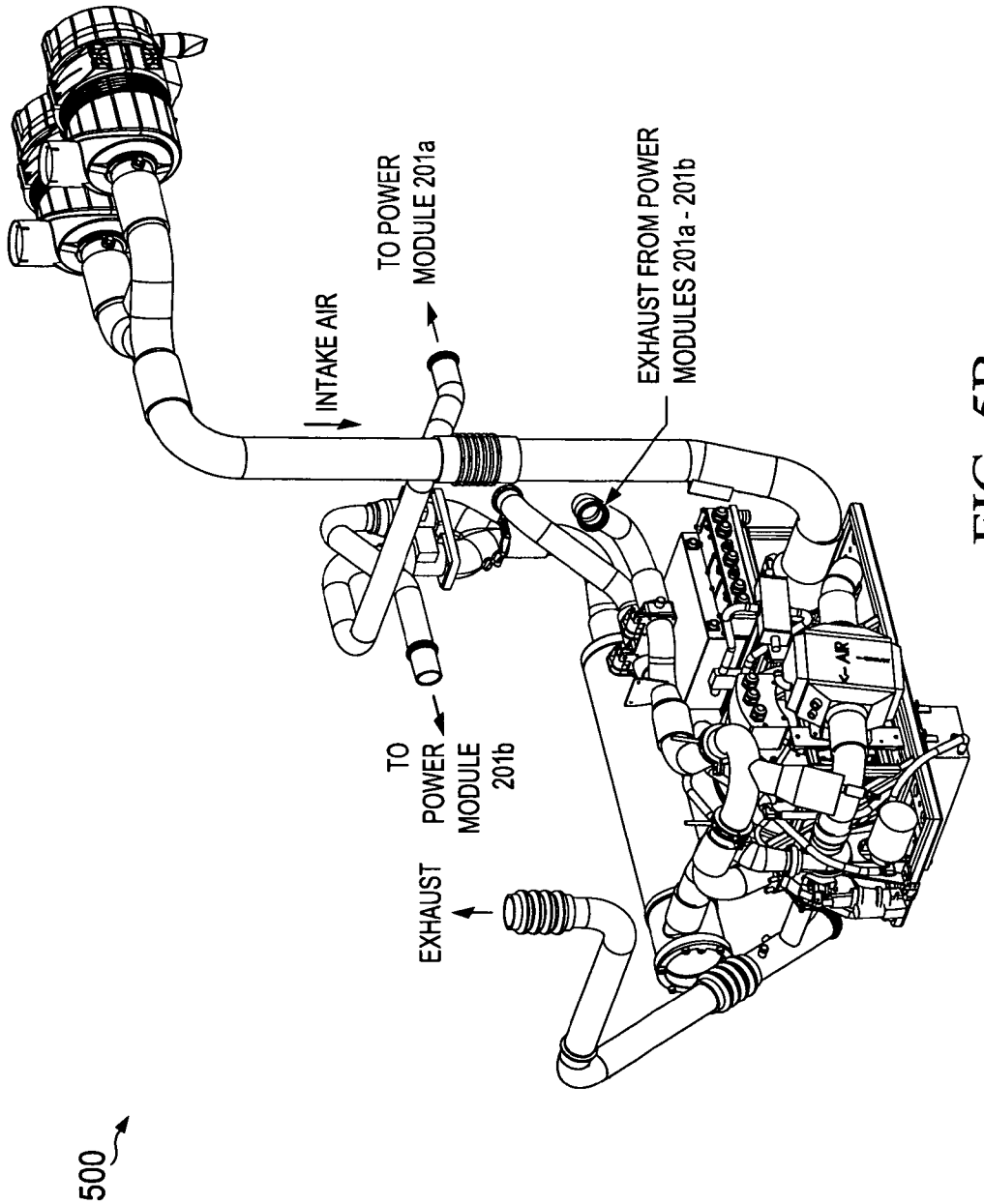
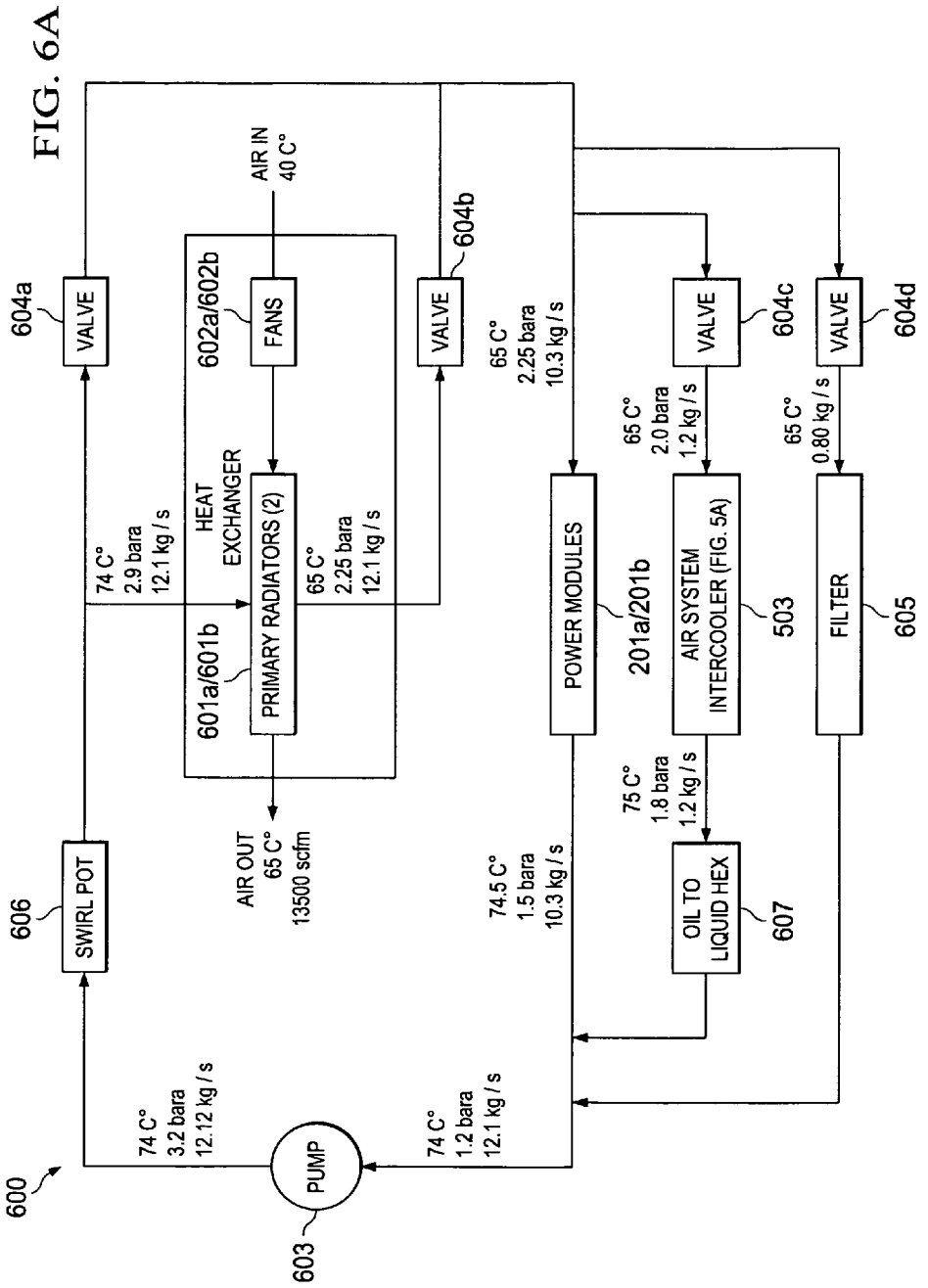

500
INTAKE AIR
TO POWER MODULE 201a
EXHAUST FROM POWER MODULES 201a - 201b
TO POWER MODULE 201b
EXHAUST

FIG. 5B

FIG. 6A


600
606
SWIRL POT
604a
VALVE
602a/602b
FANS
AIR IN
40 C°
604b
VALVE
601a/601b
HEAT
EXCHANGER
PRIMARY RADIATORS (2)
74 C°
2.9 bara
12.1 kg / s
65 C°
2.25 bara
12.1 kg / s
AIR OUT
65 C°
13500 scfm
65 C°
2.25 bara
10.3 kg / s
POWER MODULES
201a/201b
604c
VALVE
65 C°
2.0 bara
1.2 kg / s
AIR SYSTEM
INTERCOOLER (FIG. 5A)
503
604d
VALVE
65 C°
0.80 kg / s
FILTER
605
75 C°
1.8 bara
1.2 kg / s
OIL TO
LIQUID HEX
607
74.5 C°
1.5 bara
10.3 kg / s
74 C°
3.2 bara
12.12 kg / s
PUMP
603
74 C°
1.2 bara
12.1 kg / s

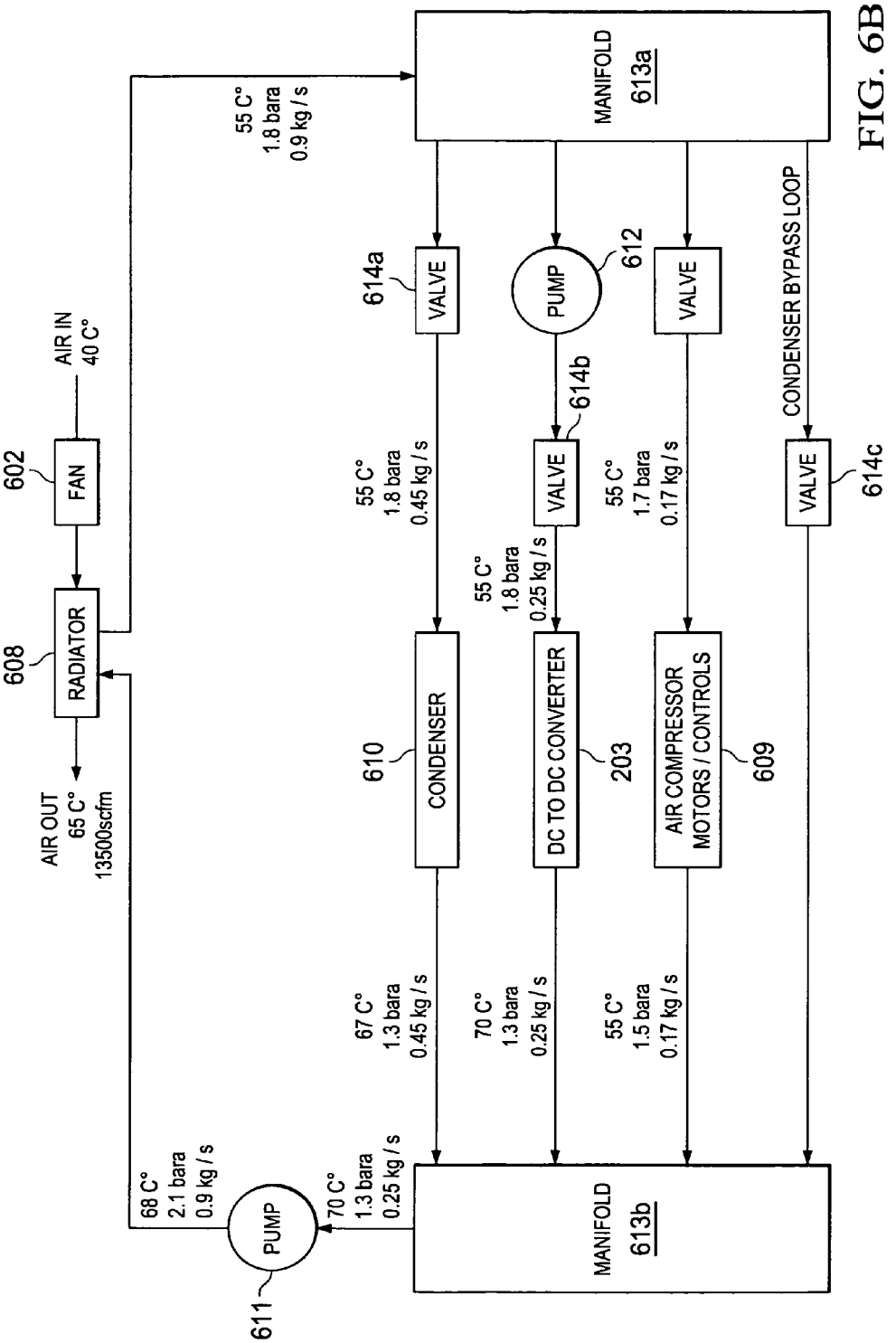

MANIFOLD
613a
55 C°
1.8 bara
0.9 kg / s
614a
VALVE
PUMP
612
VALVE
CONDENSER BYPASS LOOP
614b
VALVE
614c
55 C°
1.8 bara
0.45 kg / s
55 C°
1.8 bara
0.25 kg / s
55 C°
1.7 bara
0.17 kg / s
AIR IN
40 C°
602
FAN
608
RADIATOR
AIR OUT
65 C°
13500scfm
610
CONDENSER
203
DC TO DC CONVERTER
609
AIR COMPRESSOR
MOTORS / CONTROLS
67 C°
1.3 bara
0.45 kg / s
70 C°
1.3 bara
0.25 kg / s
55 C°
1.5 bara
0.17 kg / s
68 C°
2.1 bara
0.9 kg / s
70 C°
1.3 bara
0.25 kg / s
PUMP
611
MANIFOLD
613b

FIG. 6B

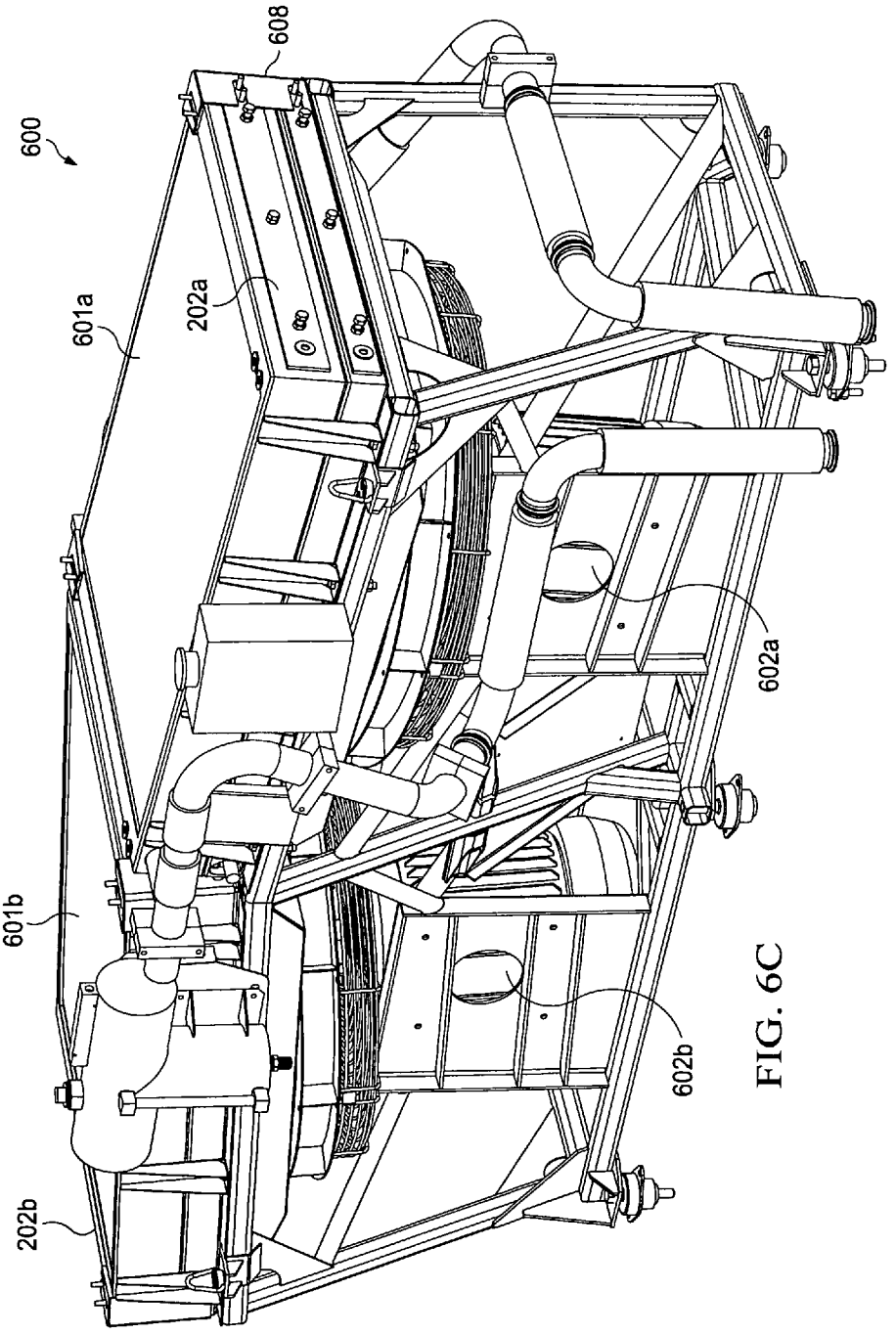


FIG. 6C

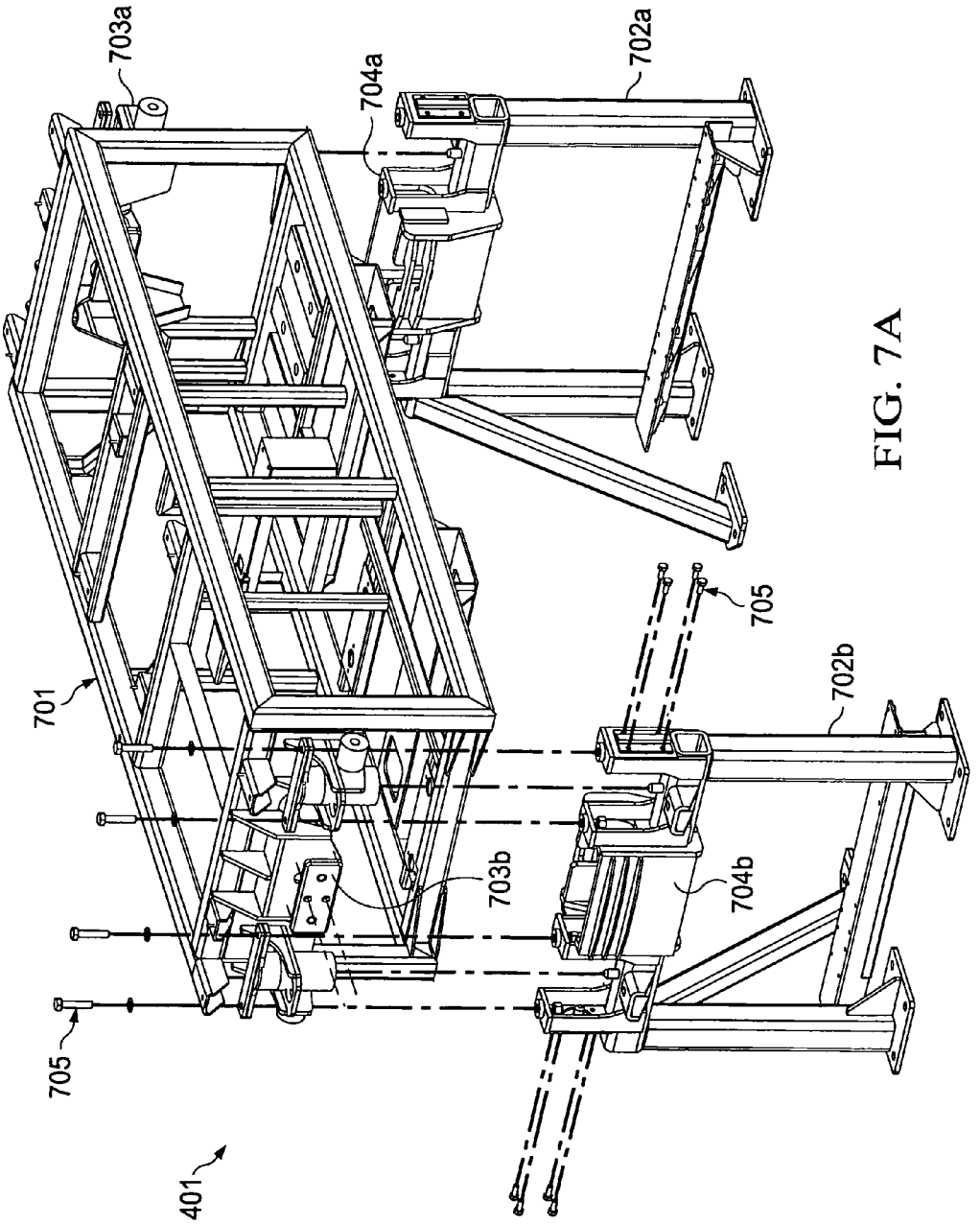


FIG. 7A

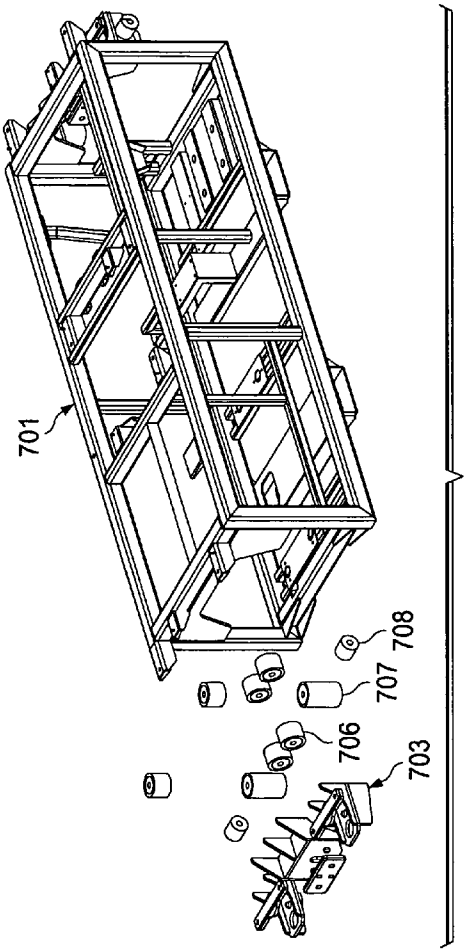


FIG. 7B

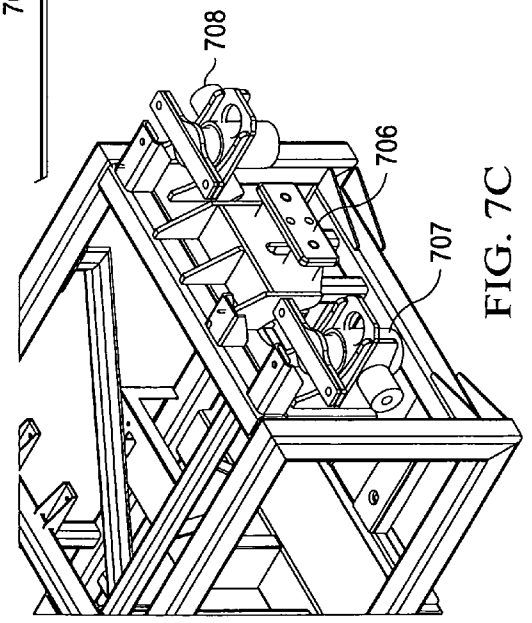


FIG. 7C

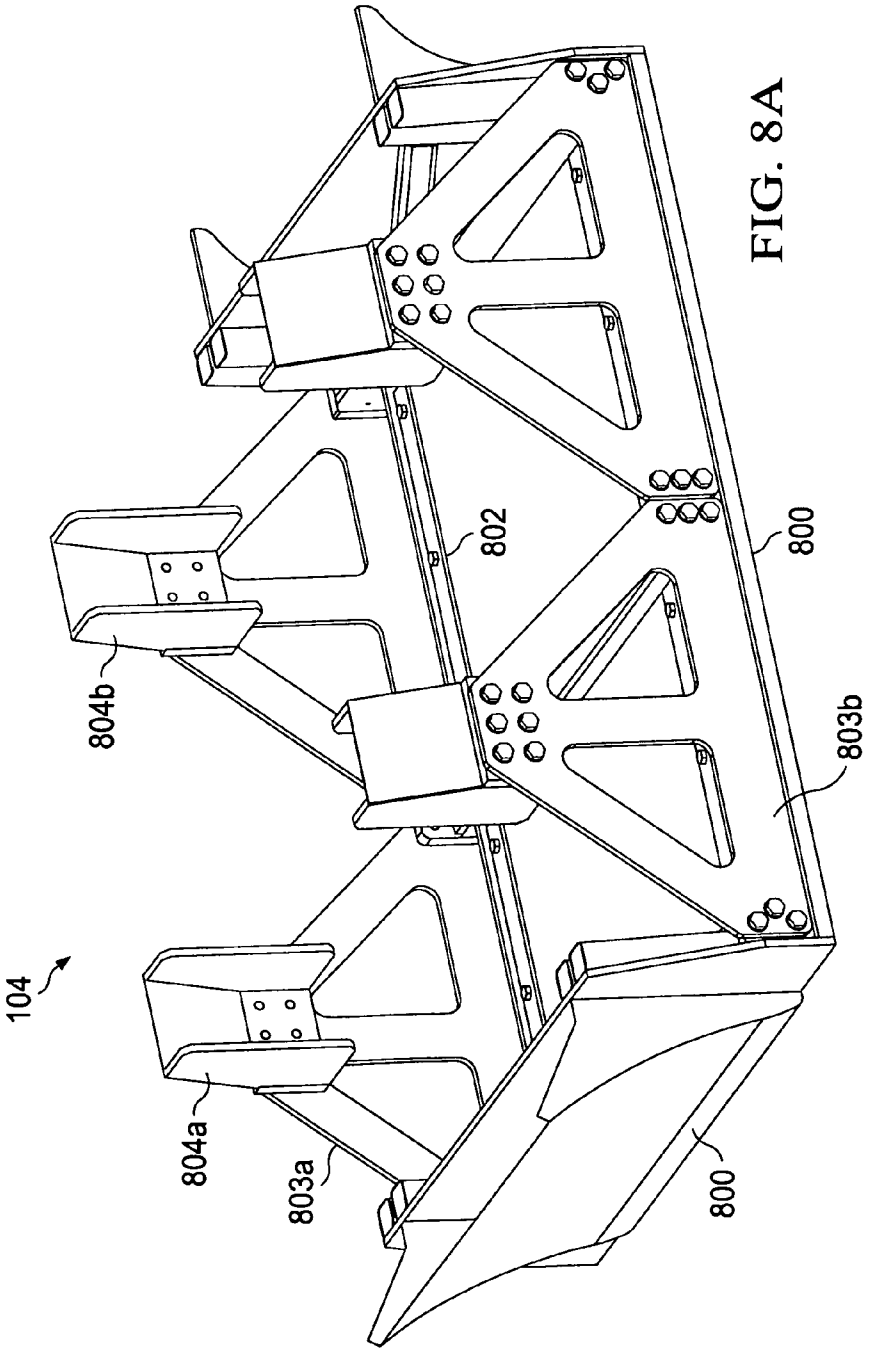


FIG. 8A

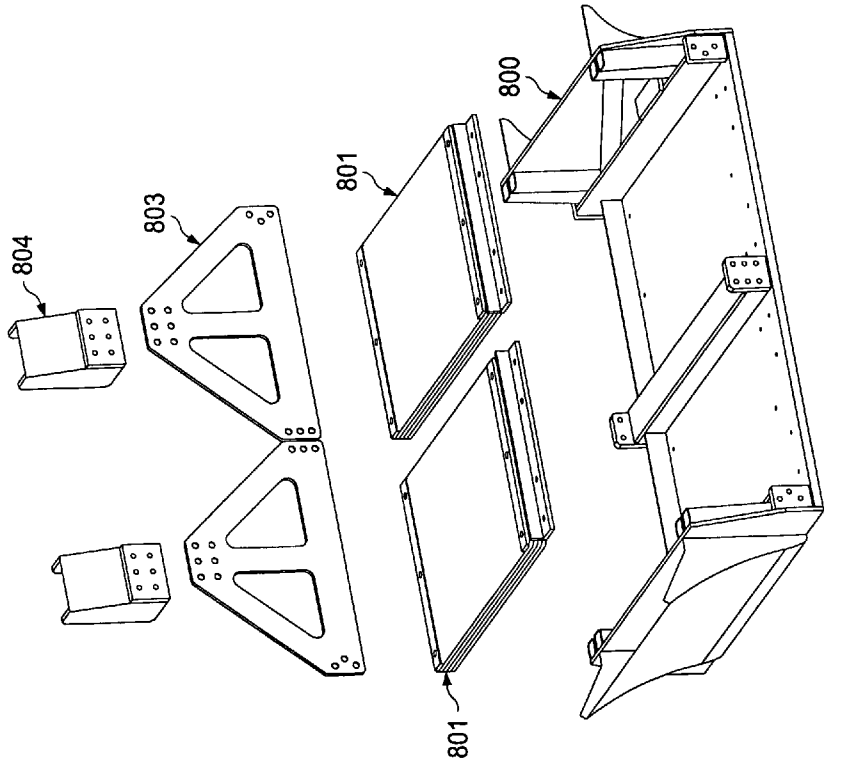


FIG. 8B

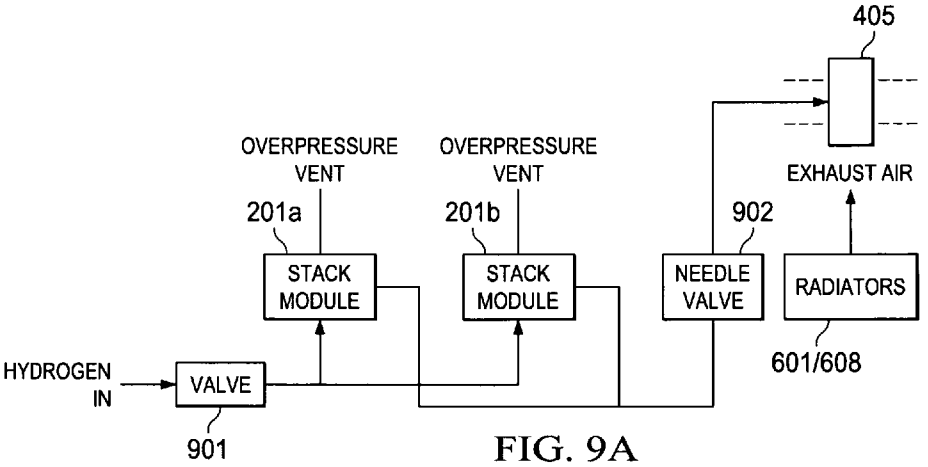

405
OVERPRESSURE VENT
OVERPRESSURE VENT
EXHAUST AIR
201a
201b
902
STACK MODULE
STACK MODULE
NEEDLE VALVE
RADIATORS
HYDROGEN IN
VALVE
601/608
901

FIG. 9A

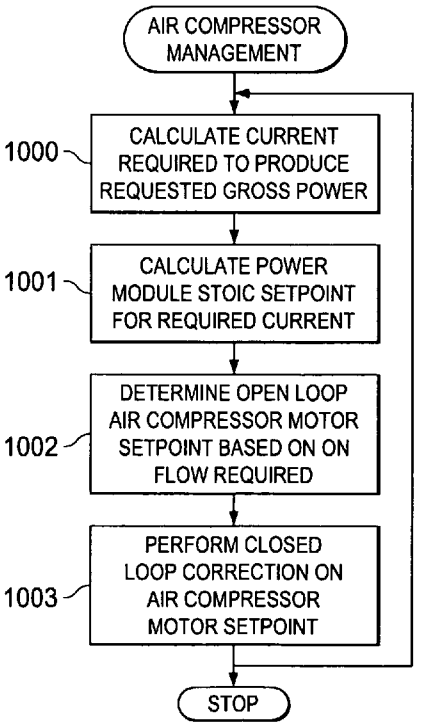

AIR COMPRESSOR MANAGEMENT
1000
CALCULATE CURRENT REQUIRED TO PRODUCE REQUESTED GROSS POWER
1001
CALCULATE POWER MODULE STOIC SETPOINT FOR REQUIRED CURRENT
1002
DETERMINE OPEN LOOP AIR COMPRESSOR MOTOR SETPOINT BASED ON ON FLOW REQUIRED
1003
PERFORM CLOSED LOOP CORRECTION ON AIR COMPRESSOR MOTOR SETPOINT
STOP

FIG. 10

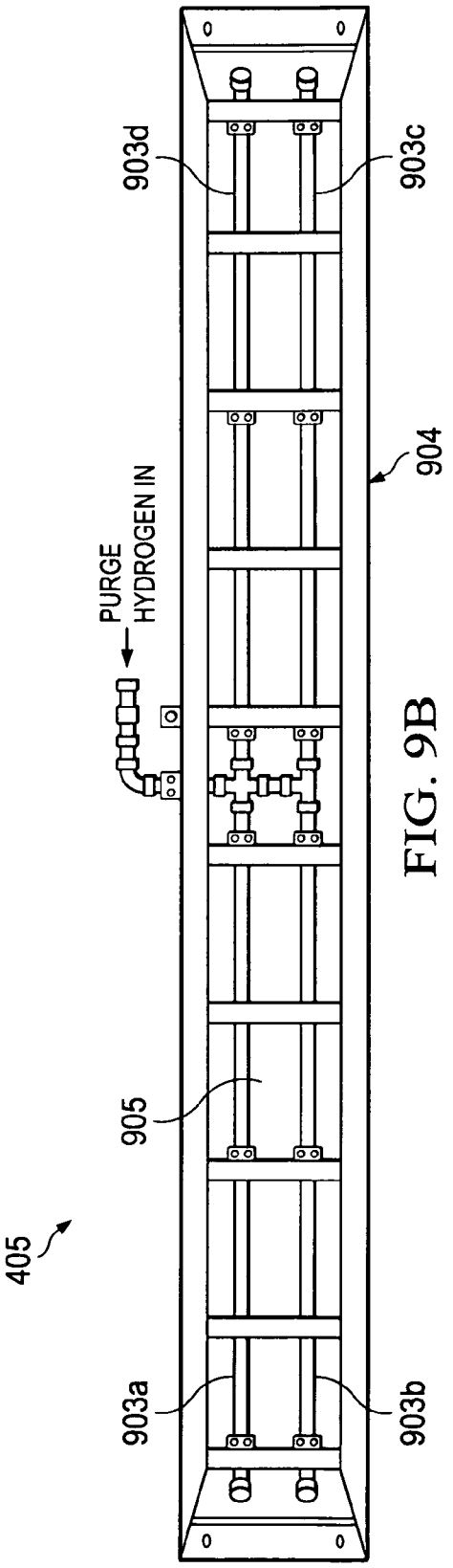


FIG. 9B

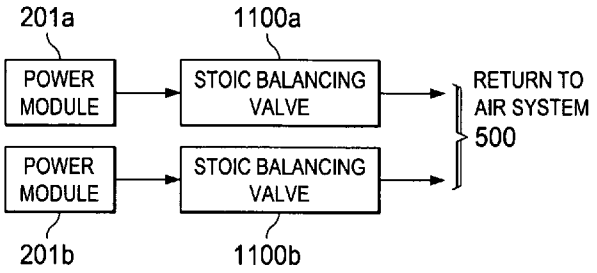


FIG. 11A

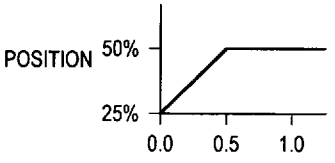


FIG. 11C

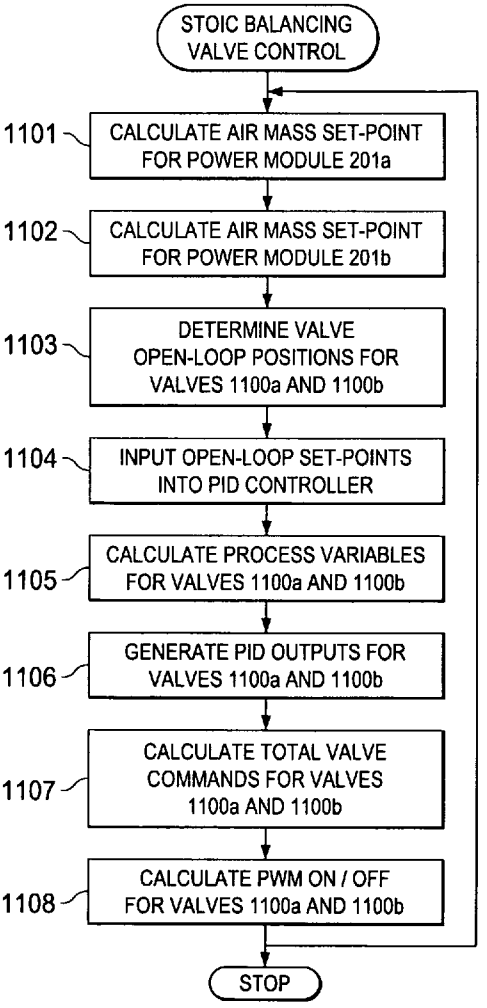


FIG. 11B

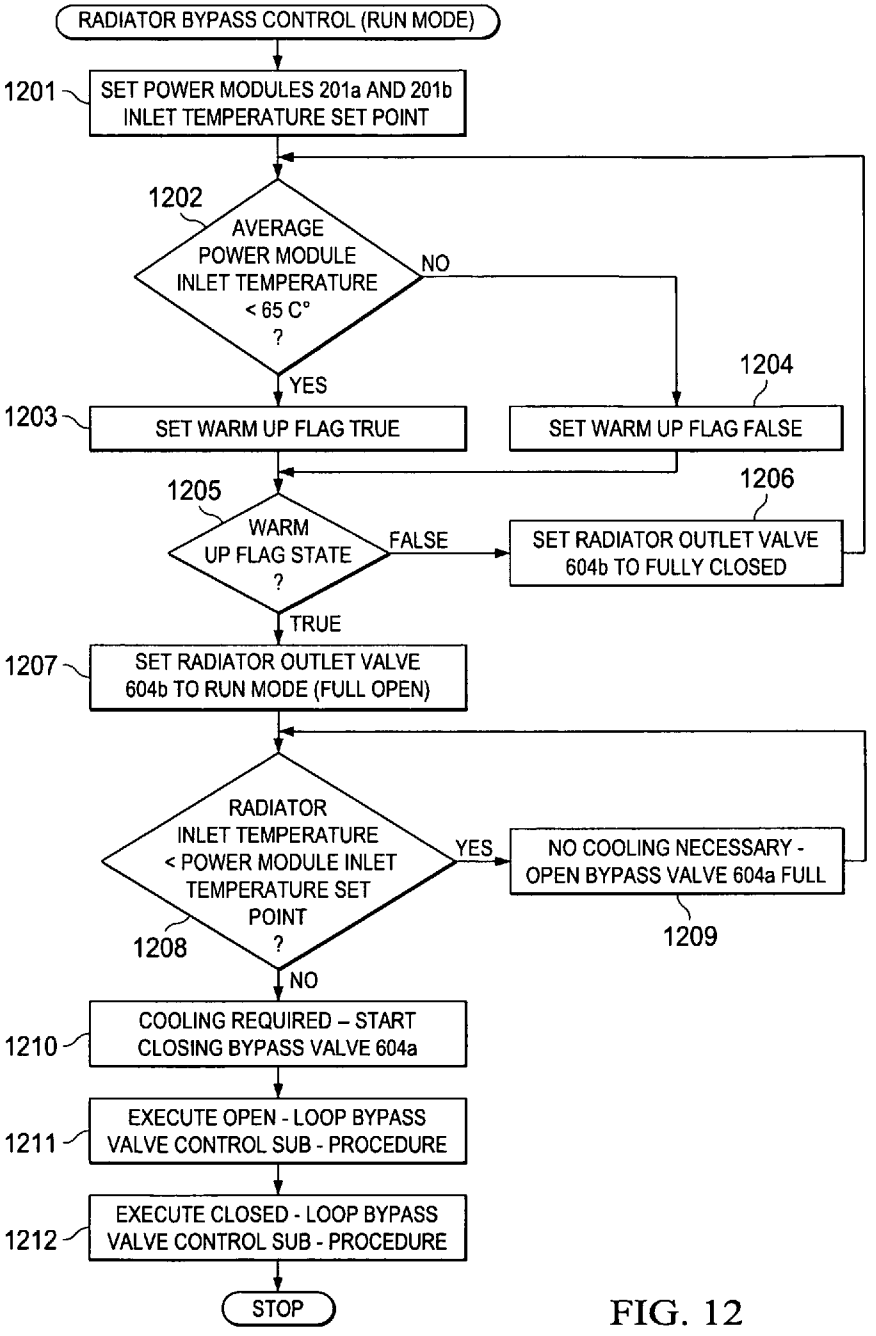

RADIATOR BYPASS CONTROL (RUN MODE)
1201
SET POWER MODULES 201a AND 201b INLET TEMPERATURE SET POINT
1202
AVERAGE POWER MODULE INLET TEMPERATURE < 65 C° ?
NO
YES
1203
SET WARM UP FLAG TRUE
1204
SET WARM UP FLAG FALSE
1205
WARM UP FLAG STATE ?
FALSE
1206
SET RADIATOR OUTLET VALVE 604b TO FULLY CLOSED
TRUE
1207
SET RADIATOR OUTLET VALVE 604b TO RUN MODE (FULL OPEN)
RADIATOR INLET TEMPERATURE < POWER MODULE INLET TEMPERATURE SET POINT ?
1208
YES
NO COOLING NECESSARY - OPEN BYPASS VALVE 604a FULL
1209
NO
1210
COOLING REQUIRED – START CLOSING BYPASS VALVE 604a
1211
EXECUTE OPEN - LOOP BYPASS VALVE CONTROL SUB - PROCEDURE
1212
EXECUTE CLOSED - LOOP BYPASS VALVE CONTROL SUB - PROCEDURE
STOP

FIG. 12

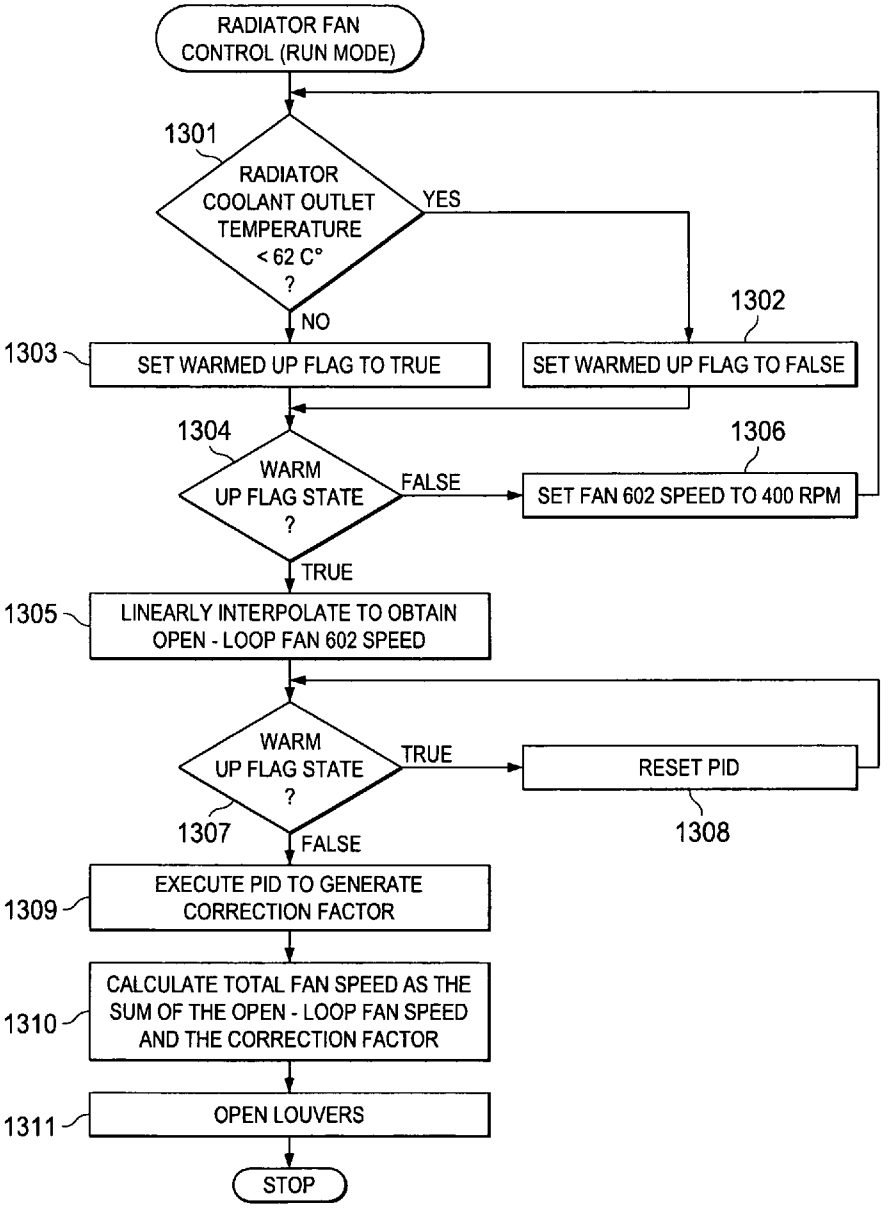

RADIATOR FAN CONTROL (RUN MODE)
1301
RADIATOR COOLANT OUTLET TEMPERATURE < 62 C° ?
YES
NO
1302
1303
SET WARMED UP FLAG TO TRUE
SET WARMED UP FLAG TO FALSE
1304
WARM UP FLAG STATE ?
FALSE
1306
SET FAN 602 SPEED TO 400 RPM
TRUE
1305
LINEARLY INTERPOLATE TO OBTAIN OPEN - LOOP FAN 602 SPEED
WARM UP FLAG STATE ?
TRUE
RESET PID
1307
1308
FALSE
1309
EXECUTE PID TO GENERATE CORRECTION FACTOR
1310
CALCULATE TOTAL FAN SPEED AS THE SUM OF THE OPEN - LOOP FAN SPEED AND THE CORRECTION FACTOR
1311
OPEN LOUVERS
STOP

FIG. 13

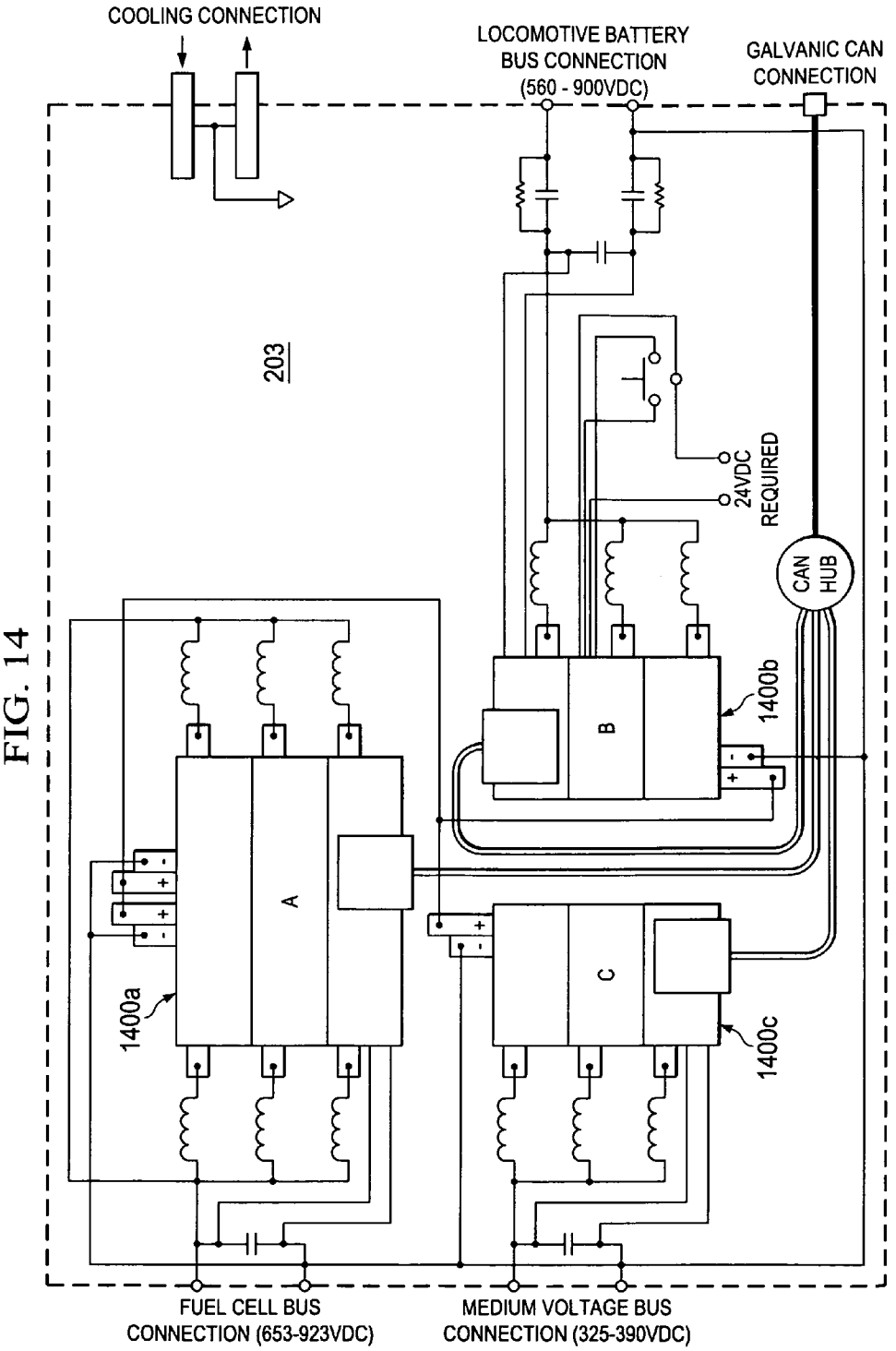

COOLING CONNECTION
LOCOMOTIVE BATTERY BUS CONNECTION (560 - 900VDC)
GALVANIC CAN CONNECTION
203
24VDC REQUIRED
CAN HUB
1400b
B
A
C
1400a
1400c
FUEL CELL BUS CONNECTION (653-923VDC)
MEDIUM VOLTAGE BUS CONNECTION (325-390VDC)

FIG. 14

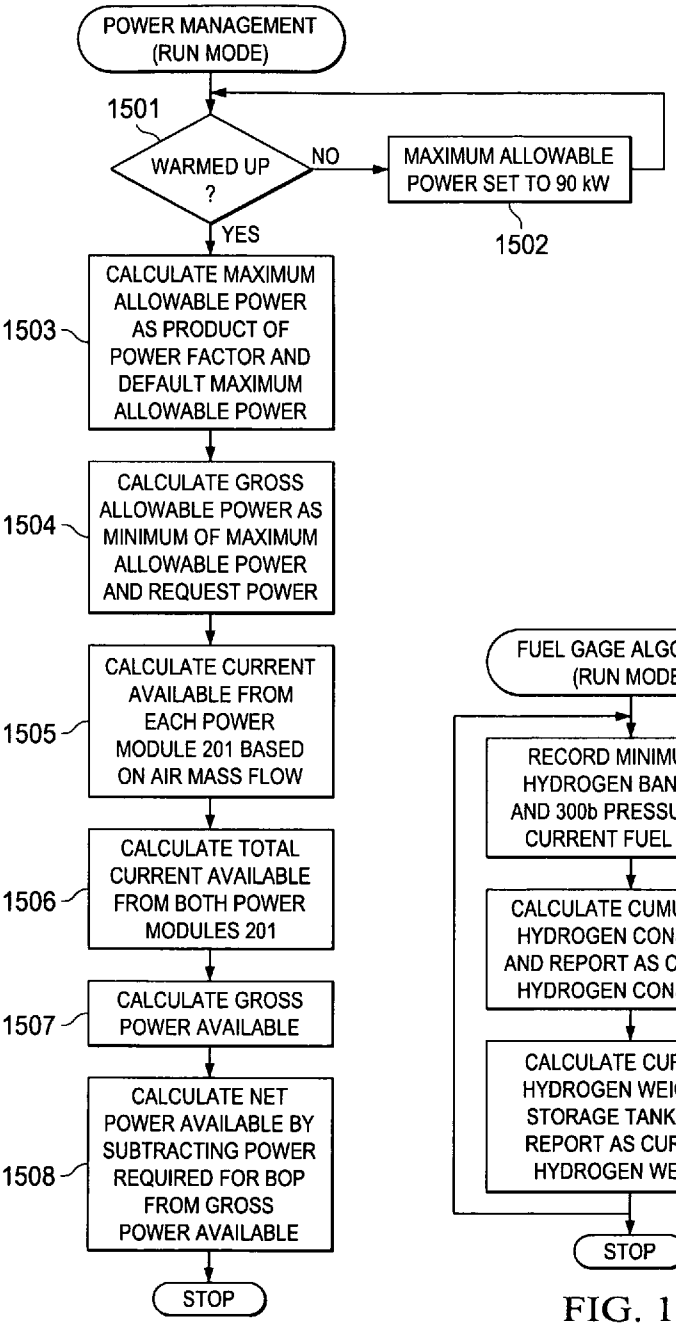

POWER MANAGEMENT (RUN MODE)
1501
WARMED UP ?
NO
MAXIMUM ALLOWABLE POWER SET TO 90 kW
1502
YES
CALCULATE MAXIMUM ALLOWABLE POWER AS PRODUCT OF POWER FACTOR AND DEFAULT MAXIMUM ALLOWABLE POWER
1503
CALCULATE GROSS ALLOWABLE POWER AS MINIMUM OF MAXIMUM ALLOWABLE POWER AND REQUEST POWER
1504
CALCULATE CURRENT AVAILABLE FROM EACH POWER MODULE 201 BASED ON AIR MASS FLOW
1505
CALCULATE TOTAL CURRENT AVAILABLE FROM BOTH POWER MODULES 201
1506
CALCULATE GROSS POWER AVAILABLE
1507
CALCULATE NET POWER AVAILABLE BY SUBTRACTING POWER REQUIRED FOR BOP FROM GROSS POWER AVAILABLE
1508
STOP

FIG. 15

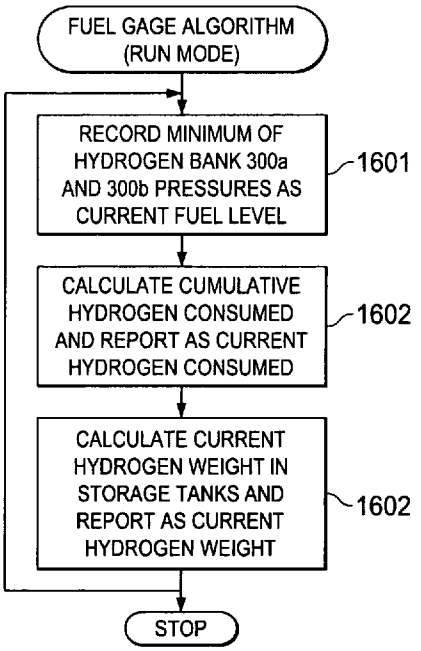

FUEL GAGE ALGORITHM (RUN MODE)
RECORD MINIMUM OF HYDROGEN BANK 300a AND 300b PRESSURES AS CURRENT FUEL LEVEL
1601
CALCULATE CUMULATIVE HYDROGEN CONSUMED AND REPORT AS CURRENT HYDROGEN CONSUMED
1602
CALCULATE CURRENT HYDROGEN WEIGHT IN STORAGE TANKS AND REPORT AS CURRENT HYDROGEN WEIGHT
1602
STOP

FIG. 16

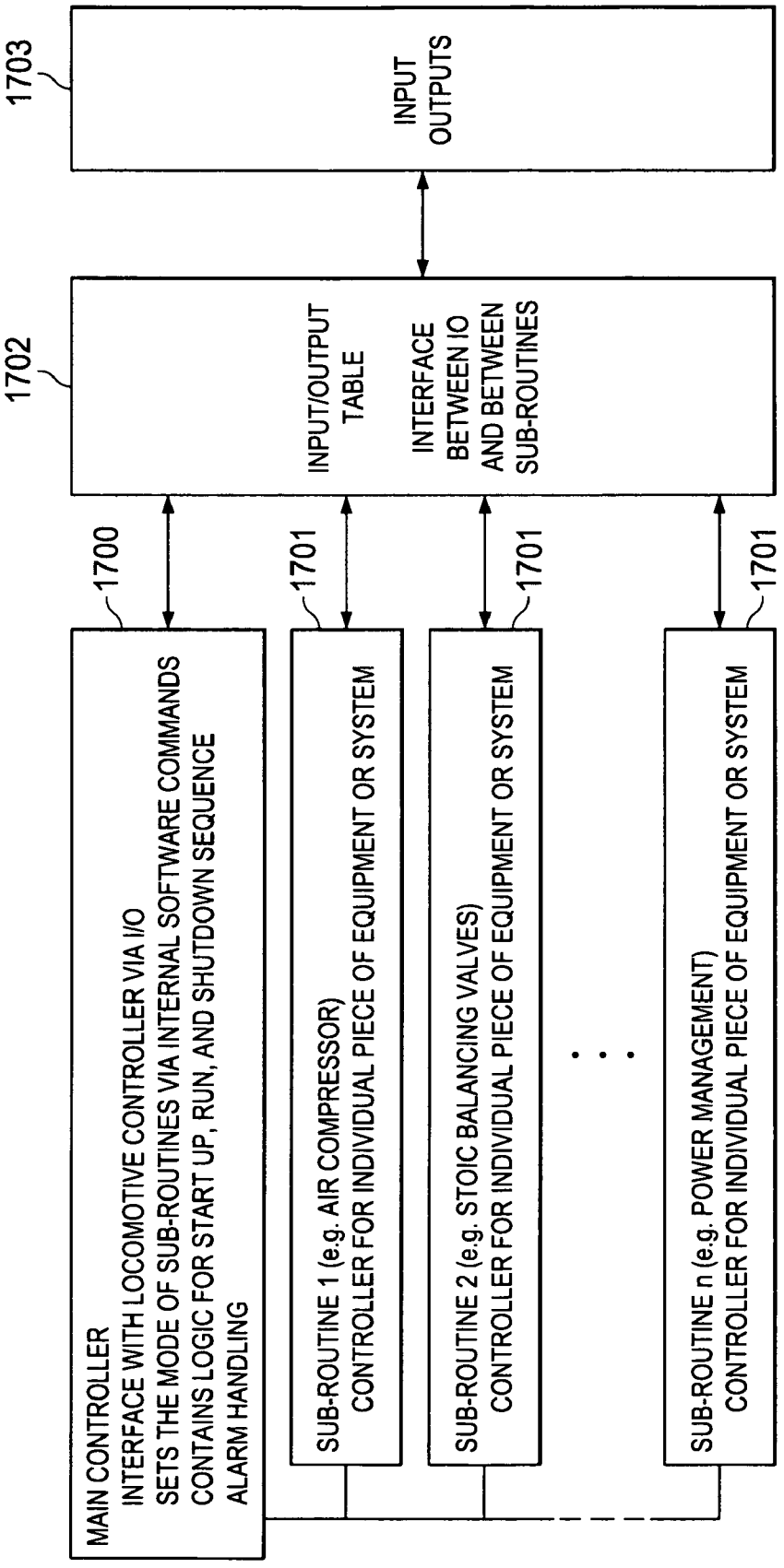

1703
INPUT OUTPUTS
1702
INPUT/OUTPUT TABLE
INTERFACE BETWEEN IO AND BETWEEN SUB-ROUTINES
1700
1701
1701
1701
MAIN CONTROLLER
INTERFACE WITH LOCOMOTIVE CONTROLLER VIA I/O
SETS THE MODE OF SUB-ROUTINES VIA INTERNAL SOFTWARE COMMANDS
CONTAINS LOGIC FOR START UP, RUN, AND SHUTDOWN SEQUENCE
ALARM HANDLING
SUB-ROUTINE 1 (e.g. AIR COMPRESSOR)
CONTROLLER FOR INDIVIDUAL PIECE OF EQUIPMENT OR SYSTEM
SUB-ROUTINE 2 (e.g. STOIC BALANCING VALVES)
CONTROLLER FOR INDIVIDUAL PIECE OF EQUIPMENT OR SYSTEM
SUB-ROUTINE n (e.g. POWER MANAGEMENT)
CONTROLLER FOR INDIVIDUAL PIECE OF EQUIPMENT OR SYSTEM

FIG. 17

HYDROGEN FUEL CELL HYBRID LOCOMOTIVES

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Patent Application Ser. No. 61/137,950, filed Aug. 5, 2008.

FIELD OF INVENTION

The present invention relates in general to railroad locomotives, and in particular to, hydrogen fuel cell hybrid locomotives.

BACKGROUND OF INVENTION

Railroads remain one of the most efficient means for transporting freight and passengers over relatively long distances. Yet, like many industries, the railroad industry is facing numerous challenges related to the upward trend in the cost of fossil fuels and increasing pressure to limit the impact of trains on the environment. The root cause for many of these challenges is the propulsion systems traditionally used in railroad locomotives.

Diesel-electric locomotives employ a diesel engine to drive an electric power generator, which in turn drives a set of traction motors that rotate the locomotive wheels. Diesel-electric locomotives have the advantage of requiring a minimal amount of support infrastructure and thus are particularly suited for providing transport across remote geographical regions. On the other hand, because diesel-electric locomotives consume diesel, they contribute to urban air pollution and are subject to operating costs tied directly to the cost of oil.

Catenary-electric locomotives run directly from an electricity source, typically electric lines running above the railroad tracks. Catenary-electric locomotives are cleaner-operating on a locomotive-by-locomotive basis than diesel-electric locomotives; however, catenary-electric locomotives must be viewed as small parts of a much larger distributed power system, which includes an electricity generation plant, transformers, and a system of transmission lines required to bring electricity to the locomotives as they run down the tracks. This large distributed power system is typically unsuitable for remove geographic regions and overall is less efficient than a system utilizing diesel locomotives.

Railroad locomotives come in different sizes and configurations, depending on the specific task they are required to perform. For example, line-haul freight locomotives, which are commonly seen running along the rail-lines in the U.S., are larger and more powerful systems designed to move fully assembled trains over long distances. On the other hand, switch locomotives ("switchers") are smaller systems primarily used in rail yards for moving cars during the assembly and disassembly of trains. In any case, locomotive designs must be robust, given the day to day stresses to which locomotives are subjected.

Alternative locomotive propulsion systems, which address the problems with diesel-electric and catenary-electric propulsion systems, would be a significant benefit to the railroad industry. However, any such alternative systems must be capable of meeting the rigors experienced by locomotives everyday, including the shock loads generated during the coupling of rail cars. Additionally, propulsion systems that

are applicable to different types of locomotives (e.g. line-haul freight locomotives and switchers) would be an additional and significant advantage.

SUMMARY OF INVENTION

The principles of the present invention are embodied in a hydrogen hybrid locomotive including a set of batteries for driving a plurality of electric traction motors for moving the locomotive along a set of railroad rails and a fuel cell power plant for charging the set of batteries and driving the electric traction motors. The fuel cell power plant includes at least one fuel cell power module for generating electrical current by reacting hydrogen fuel and oxygen from intake air, the amount of electrical current generated being proportional to an air mass flow of the intake air. An air system selectively provides an air mass flow to the fuel cell module to generate an amount of electrical current required for corresponding operating conditions of the locomotive. A cooling system cools the at least one fuel cell power module in response to the amount of current being generated.

The embodiments of the principles of the present invention address a number of technical problems related to weight, center of gravity, packaging, and safety, not found in the development of hydrogen hybrid fuel cell propulsion systems for smaller vehicles. As a result, a number of significant advantages can be realized as hydrogen hybrid fuel cell locomotives embodying the principles of the present invention are deployed. Among other things, such hydrogen hybrid fuel cell locomotives help reduce particulate air pollution in urban rail yards, as well as reduce the amount of greenhouse gases expelled into the atmosphere. Furthermore, the use of hydrogen as a fuel reduces the dependency of the railroads on imported oil and decouples locomotive operating costs from the volatile fossil fuel markets. Moreover, hydrogen hybrid fuel cell locomotives can act as mobile electricity sources, for example in disaster recovery scenarios.

BRIEF DESCRIPTION OF DRAWINGS

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIGS. **1**A-**1**D are respectively left-side, top, front, and rear views of a representative hydrogen fuel cell hybrid locomotive embodying the principles of the present invention;

FIG. **2** is a diagram showing the integration of a hydrogen fuel cell system into the hydrogen hybrid locomotive **100** of FIGS. **1**A-**1**D;

FIG. **3** is diagram showing a preferred method of mounting the hydrogen tanks of FIG. **2** to the battery racks;

FIG. **4** is a diagram illustrating the fuel cell power plant, as mounted on its isolating support structure;

FIG. **5**A is a block diagram of air system **500**, which provides air to the power modules of the power plant of FIG. **4**;

FIG. **5**B is a diagram of the mechanical structure of air system shown in FIG. **5**A;

FIG. **6**A is a block diagram of the primary cooling loop of the cooling system, which provides coolant to the power modules and air system of the power plant of FIG. **4**;

FIG. **6**B is a block diagram of the secondary cooling loop of the cooling system, which provides coolant to the DC to DC converter of FIG. **2** and various auxiliary systems;

FIG. **6**C is a diagram showing front and back views of the physical structure of the cooling system;

FIG. **7**A-**7**C are a series of views illustrating the isolating support structure of FIG. **4** in further detail;

FIGS. **8**A and **8**B are detailed diagrams of the adjustable ballast system of FIG. **1**A;

FIG. **9**A is a block diagram showing the power module purge system, with FIG. **9**B providing a more detailed view of the purge diffuser of FIGS. **4** and **9**A.

FIG. **10** is a block diagram illustrating a preferred algorithm for controlling the air compressor speed and torque and the air being provided to the power modules;

FIG. **11**A is a block diagram illustrating the relationship between the power modules and the stoic balancing valves;

FIG. **11**B is a flow chart of a preferred stoic balancing valve control algorithm;

FIG. **11**C is a curve characterizing the control of the power module stoic balancing valves;

FIG. **12** is a flow chart of a preferred radiator bypass control algorithm;

FIG. **13** is a flow chart of a preferred radiator fan control algorithm;

FIG. **14** is a block diagram of the DC to DC converter of FIG. **2**;

FIG. **15** is a flow chart of a preferred power management algorithm;

FIG. **16** is a block diagram of a preferred fuel gage algorithm; and

FIG. **17** is a block diagram of the programmable automation controller which, among other things, executes the various control algorithms.

DETAILED DESCRIPTION OF THE INVENTION

The principles of the present invention and their advantages are best understood by referring to the illustrated embodiment depicted in FIGS. **1**-**17** of the drawings, in which like numbers designate like parts.

FIGS. **1**A-**1**D are respectively left-side, top, front, and rear views of a hydrogen fuel cell hybrid ("hydrogen hybrid") switching locomotive **100** embodying the principles of the present invention. It should be recognized that while the principles of the present invention are being described with respect to a switching locomotive embodiment, these principles are applicable to the design and construction of line-haul locomotives, as well.

The various components and subsystems of hydrogen hybrid locomotive **100** will be discussed in detail below. Generally, hydrogen hybrid locomotive **100** includes a cab section **101** containing the control systems used by the operator, a center section **102** containing the batteries and the hydrogen storage tanks, a rear housing section **103** containing the hydrogen fuel cell power plant, and an adjustable ballast section **104** disposed under the locomotive chassis.

The rear housing **103** includes a set of configurable louvers **105** above the cooling module, which, under the control of the locomotive electronic control systems, allows cooling module fans to exhaust and dilute the purged hydrogen which is expelled through the diffuser mounted above the louvers.

Generally, hydrogen hybrid locomotive **100** weighs approximately 280,000 pounds (127 tonnes) and operates from a set of batteries and a proton exchange membrane (PEM) fuel cell power plant, which together provide a continuous power of 250 kW and a transient power of at least 1 MW. In the preferred embodiment, the basic locomotive platform is based on a Green Goat™ diesel-battery hybrid switch engine commercially available from Railpower Technologies Corp. The PEM fuel cells are available from Ballard Power Systems Inc.

One primary factor in the design of hydrogen hybrid locomotive **100** is the duty cycle P(t), where P is the vehicle power, and t is the time recorded from an in-service yard switching locomotive. From the duty cycle P(t), the locomotive required mean power, maximum power, power response time, and power duration are calculated. The energy storage requirements are calculated from the integral of P(t).

For a typical switch locomotive, the peak power reaches 600-1000 kW for durations of no more than several minutes, normally when train cars are accelerated or the locomotive travels uphill. On the other hand, the required power is minimal when the locomotive is idling between car move operations. Idle time usually accounts for 50-90% of the operations schedule of a typical switch locomotive. In the design of hydrogen hybrid locomotive **100**, an analysis of the duty cycles of typical switching locomotives in various switch yards showed that the combination of long idle periods and short peak power periods resulted in a mean power usage in the range of only 40-100 kW.

In hydrogen hybrid locomotive **100**, the hydrogen fuel must be capable of providing at the mean power of the duty cycle. Additionally, in hydrogen hybrid locomotive **100**, lead acid batteries provide the auxiliary power/energy storage. These lead acid batteries must be capable of storing sufficient energy to provide power, at a minimum, from the rated continuous power up to the peak required power of around **1100** kW for the illustrated embodiment.

At the same time, the power and energy provided by the batteries must not exceed a relatively shallow depth of discharge such that the size of the batteries can be minimized. Depth of discharge is a function of acceptable battery cycle life and recharge rate. In the illustrated embodiment, the depth of discharge of the lead acid batteries is limited to approximately 80% of full capacity.

FIG. **2** is a diagram showing the integration of the fuel cell system into hydrogen hybrid locomotive **100**. Rear housing **103** includes a hydrogen fuel cell power plant based on two (2) power (stack) modules **201***a* and **201***b*, along with corresponding ethylene glycol cooling systems **202***a* and **202***b* and a DC to DC power converter **203**.

Hydrogen is provided to power modules **201***a*-**201***b* from fourteen (14) carbon-fiber composite tanks **204**, which collectively store approximately 70 kg of hydrogen at 350 bar. Hydrogen tanks **204** are disposed above lead-acid batteries **205**. Power from fuel cell DC to DC converter **203** and batteries **205** is distributed through a high-voltage bus system **207** to various locomotive systems, including displays **208***a* and **208***b* and 600 VDC traction motors **209***a*-**209***d*.

FIG. **3** is a diagram showing a preferred method of mounting hydrogen tanks **204**. As a shown in FIG. **3**, hydrogen tanks **204** are partitioned into two (2) hydrogen storage modules **300***a* and **300***b*, each consisting of seven (7) carbon fiber/aluminum tanks (cylinders) **204** that collectively store approximately 35 kg of compressed hydrogen. The total amount of hydrogen available through both hydrogen modules **300***a* and **300***b* is approximately 70 kg at 350 bar. Each hydrogen storage module **300** is mounted on a corresponding mounting frame **301***a*-**301***b* and battery rack **302***a*-**302***b*.

Advantageously, by mounting hydrogen tanks **204** at the top of hydrogen hybrid locomotive **100**, any hydrogen escaping due to a leak harmlessly dissipates upward. (In contrast, storing hydrogen below void volumes could result in hydrogen confinement and an increased possibility of detonation.) Furthermore, locating hydrogen tanks towards the top of the locomotive minimizes the likelihood of damage in a derailment or by impact with track debris or yard traffic.

Hydrogen tanks **204** are preferably carbon fiber/aluminum tanks, which measure 416 mm diameter and 2100 in length, and weigh approximately 100 kg. Each tank includes an excess flow valve, two thermally activated pressure relief devices (PRD), a temperature sensor, an electronically controlled solenoid valve and a manual shut-off valve. The excess flow valve closes in the event of a line rupture between the given tank and the corresponding manifold. Each thermally activated TRD vents hydrogen through a venting line, routed upward and away from hydrogen hybrid locomotive **100**, upon the detection of heat in excess of approximately 109° C. (which may occur, for example, in the event of a battery fire). The temperature sensors are also used to regulate refueling speed. The electronic solenoid valve, which is normally closed, is powered open in the run and defueling modes, and closed if a high-level system fault is detected.

The individual tanks **204** feed a corresponding module manifold **303***a* or **303***b*, each of which is provided with an independent pressure sensor, which is connected to a primary distribution line. The primary distribution line includes an excess-flow valve for controlling any ruptures. In turn, primary distribution line connects to a refueling line, and then to a filter, pressure regulator, additional electronic solenoid valve, pressure sensor, and an additional PRD. The additional solenoid valve adds a layer of shutdown capability, while the pressure sensor verifies regulator functionality. Emergency shutoff devices located on both sides of hydrogen hybrid locomotive **100** allow non-operators or refueling personnel to shut down the system.

As stated above, hydrogen hybrid locomotive **100** is based on a commercially available diesel-hybrid donor platform. Consequently, because hydrogen tanks **304** are relatively light in weight (i.e. approximately 100 kg); they have minimal effect on the locomotive center of gravity. However, ballast of approximately 9000 kg is required in the undercarriage to provide a locomotive weight of 127 tonnes, which is necessary to produce sufficient wheel adhesion to support tractive effort.

FIG. **4** provides an overall view of power plant **400**, which produces electric power from hydrogen and air. Power plant **400**, which is supported by isolating support structure **401**, includes power modules **201***a* and **201***b*, corresponding cooling modules **403***a*-**403***b*, and the balance of the plant (BOP) **404**, which includes the air system and water management equipment. DC to DC converter **203** is disposed under support structure **401**. A purge diffuser **405** sits above cooling modules **403***a*-**403***b* and is disposed within the exhaust air flow of the cooling system radiators, as discussed in detail below.

In the illustrated embodiment, power modules **201***a*-**201***b* are based on Ballard Power Systems Mk903 PEM fuel cell stacks. Each power module **201***a*-**201***b* is rated at 150 kW gross power at 624 VDC, such that power plant **400** provides a total of 300 kW gross power a 624 VDC. Each power module **201***a*-**201***b* also includes various systems for air and hydrogen humidification, water recovery, hydrogen recirculation, and hydrogen purge. Hydrogen is supplied from hydrogen tanks **204** at a nominal pressure of 12 bars absolute (bara) and is re-circulated within the corresponding stack.

FIG. **5**A is a block diagram illustrating air system **500**, which provides air to power modules **201***a* and **201***b* at a pressure of approximately 3 bara and a maximum mass flow of approximately 300 gs^{-1}. The physical structure of air system **500**, for the preferred embodiment of hydrogen hybrid locomotive **100**, is shown in FIG. **5**B. It should be noted that the pressures and temperatures provided in FIG. **5**A are exemplary values based on calculations for the illustrated embodiment of hydrogen hybrid locomotive **100** and may vary in actual physical embodiments of air system **500**, as well as in different embodiments of hydrogen hybrid locomotive **100**.

Intake air is first passed though a filter **501** and then an air compressor **502**, which provides the first stage of a two-stage compression system. In the illustrated embodiment, air compressor is a twin-screw compressor driven by an 55 kW (360 VDC) electric motor.

The air flow output from air compressor **502** is then cooled by a liquid-to-air intercooler **503**, which receives WEG cooling liquid from the cooling system (discussed in detail below). The air flow from intercooler **503** is passed though a turbocharger **504** that provides the second stage in the air compression process. Turbocharger **504** is driven by exhaust air from power modules **201***a* and **201***b* and controls system back pressure, as well as provides an additional boost in pressure. The output from turbocharger **504** is filtered by filter **505** before delivery to the inlets of power modules **201***a*-**201***b*.

Cooling system **600**, which is implemented by cooling modules **202***a* and **202***b* of FIG. **2**, is based on two independent cooling loops. A primary cooling loop, as shown in the block diagram of FIG. **6**A, provides coolant to power modules **201***a*-**201***b* and air system intercooler **503**. A secondary cooling loop, shown in the block diagram of FIG. **6**B, provides coolant to DC to DC converter **203** and various auxiliary systems, such as the air compressor motor. FIG. **6**C is a diagram showing side views of the physical structure of cooling system **600**. In FIGS. **6**A and **6**B, the given pressures, temperatures, and flow rates are exemplary values based on calculations for the illustrated embodiment of hydrogen hybrid locomotive **100** and may vary in actual physical embodiments of cooling system **600**, as well as in different embodiments of hydrogen hybrid locomotive **100**.

The primary cooling system shown in FIG. **6**A is based on a pair of primary radiators **601**, a corresponding pair of fans **602**, and a pump **603**. Additionally, the primary loop includes a mixed bed ion-exchange resin to maintain de-ionization of the 50% water-50% ethylene glycol (WEG) cooling liquid. A set of flow control valves **604***a*-**604***d* control fluid flow through the various other subsystems. Valves **604***a* and **604***b* in particular allow for bypass of radiators **601** during cold start or when an increase in coolant fluid temperature is required (e.g. during cold weather operation).

In the preferred embodiment, the overall fuel cell power operating efficiency is assumed to be on the order of 50%. Consequently a heat rejection rate of approximately 300 kW is provided by cooling system **600**, mostly by primary radiators **601**.

Pump **603** is preferably a centrifugal pump driven by a 7 kW induction motor (230 VAC) and provides coolant flow of up to 675 L min^{-1}. A closed-loop control system maintains a specific coolant temperature difference between the power module inlets and the power module outlets. In the preferred embodiment, the maximum operating temperature of the primary coolant loop is 75° C.

Radiators **601** preferably utilize a two-pass cross counter flow arrangement, and are commercially available from the Modine Fuel Cell products group. Advantageously, the cross-counter flow arrangement significantly increases the logarithmic mean temperature difference and the efficiency of the radiators. In the illustrated embodiment, each radiator has dimensions that are preferably approximately 900 mm×1100 mm.

In the illustrated embodiment, each fan **602** comprises a 32 inch fan driven by a 15 kW induction motor (230 VAC) at

approximately 1700 rpm and provides approximately 13,000 CFM of air at maximum operating power at maximum ambient conditions.

The primary cooling loop also includes a filter **605** for removing particulate matter from the coolant fluid, a swirl pot **606** for coolant filling, and an oil to liquid heat exchanger **607** on the outlet of intercooler **503**.

In the secondary coolant loop shown in FIG. **6**B, a secondary radiator **608** is provided physically in line with one of the primary radiators **601** of the primary loop of FIG. **6**B and hence utilizes a single airflow path with the corresponding fan **602**. The secondary cooling loop system provides heat rejection for drive motor/controller **609** of air compressor **502**, fuel cell stack module condenser **610**, DC to DC converter **203**, and the lube system. The overall rate of rejection is approximately 40 kW, providing coolant to components at approximately 55° C.

A centrifugal pump **611**, which in the illustrated embodiment is driven by a ½ kW motor (24 VDC), provides 80 L min^{-1} of coolant at maximum power under maximum ambient conditions. A secondary pump **612** provides coolant flow to DC to DC converter **203**. For cold weather protection, the cooling system incorporates a "block heater" with a pump that heats and circulates coolant through the primary cooling loop to prevent stack freezing.

A pair of manifolds **613***a* and **613***b*, along with flow control valves **614***a*-**614***c*, control fluid flow through the various subloops of the secondary cooling loop.

FIG. **7**A-**7**C are a series of views illustrating power module support structure **401** of FIG. **4** in further detail.

As discussed above, mounting of power module **400** is of critical importance, particularly in switch locomotive embodiments of the principles of the present invention, such as hydrogen hybrid locomotive **100**. Switch locomotives are primarily used to couple together cars when forming trains, and thus are repeatedly subjected to shocks of up to 10 Gs, typically as 11 ms saw tooth waveforms. Notwithstanding the short time duration of these shocks, their magnitude is sufficient to cause immediate or fatigue failure of the components and structures of the locomotive, in the absence of properly designed isolation structures.

According to the principles of the present invention, power module mounting frame **401** utilizes set of rubber or synthetic mounts and rigid legs to reduce shock loads transmitted to power modules **201***a*-**201***b*, cooling system **600**, and air system **500**. Generally, these isolators reduce the typical switch engine 10 G shock loads to a maximum of 3 Gs and account for shock loads and vibrational energy in all of the horizontal, lateral, and vertical directions. Furthermore, the isolators absorb energy through a deflection distance that allows power module mounting frame **401** to fit within the physical constraints imposed on it by the dimensions of power plant **400**, including those of the air and coolant systems. For example, the isolation mount movement is constrained to provide space for such structures as the coolant hoses. Additionally, power module mounting frame has a natural frequency that is well below the possible disturbing frequencies generated during the operation of hydrogen hybrid locomotive **100**. Finally, power module mounting frame **401** has a vertical center of gravity that minimizes rocking motion of power module **400** and transmits force directly downward into the locomotive chassis.

As shown in FIG. **7**A, power module mounting frame **401** includes mounting frame **701**, which contain power modules **201***a* and **201***b* and BOP **404**, and two rigid end support frames **702***a*-**702***b*, which fasten to the primary frame of hybrid locomotive **100**.

Isolation brackets **703***a*-**703***b* on mounting frame **701** interface with corresponding brackets **704***a*-**704***b* on rigid end support frames **702***a*-**702***b*. In the illustrated embodiment, mounting frame **701** is fastened to end support frames **702***a*-**702***b* with bolts **705**.

FIGS. **7**B and **7**C are more detailed diagrams of power module mounting frame **401** that emphasize the preferred isolation system. Each isolation frame **703** interfaces with mounting frame **701** through a set of rubber or synthetic isolators, as discussed above. In particular, isolators **706** absorb the energy produced by longitudinal shock and vibration transmitted through end support frames **702***a*-**702***b*. Similarly, isolators **707** absorb energy from vertical shock and vibration, while isolators **708** absorb energy from lateral shock and vibration.

As discussed above, hydrogen hybrid locomotive **100** is based on a diesel hybrid locomotive from which the diesel engines and associated equipment have been removed and replaced with a hydrogen fuel cell power plant. Hydrogen hybrid locomotive **100** therefore no longer carries diesel fuel, which means that its weight is significantly under the weight required to maximize the tractive effort at the wheels. Additionally, the weight lost by the lack of diesel fuel changes the vertical center of gravity and the forward/aft weight distribution.

To ensure that hydrogen hybrid locomotive **100** is sufficiently heavy and that the vertical center of gravity and forward/after weight distribution are correct, hydrogen hybrid locomotive **100** includes adjustable ballast system **104** shown in FIG. **1**B and described in further detail in FIGS. **8**A and **8**B. Adjustable ballast system **104** also provides usable space under the locomotive main frame for additional equipment such as air compressors, fans, power electronics, and the like.

As shown in FIGS. **8**A and **8**B, adjustable ballast system **104** includes a base structure **800**, which is preferably a pre-welded assembly that welds to the locomotive primary frame structure. A plate assembly **801**, including multiple sheets of thick steel, is bolted into base structure **800** with bolts **802**. Two sets of plates are preferably used that allow individual steel plates to be added, removed, or moved for and aft to adjust the amount and location of the ballast weight. A-gusset assemblies **803***a* and **803***b*, each of which includes flanges **804***a* and **804***b*, bolt to both base structure **800** and the locomotive primary frame. A-gusset assemblies **803***a*-**803***b* advantageously provide bending stiffness to adjustable ballast assembly **104**, as well as provide bolt-on/off access to equipment mounted above the plate assembly.

Hydrogen is supplied and purged from power modules **201***a* and **201***b* using the supply and purge system shown in the block diagram of FIG. **9**A. During supply, hydrogen is provided to power modules **201***a*-**201***b* through control valve **901**. During hydrogen purge, in which hydrogen may be exiting from power modules **201***a*-**201***b* at pressures of up to 3 bara, purged hydrogen passes through a purge tuning needle valve **902** and on to purge diffuser **405** (FIG. **4**). Exhaust air exiting the coolant system radiators **601**/**608** dissipates the hydrogen output from diffuser **405**.

FIG. **9**B provides a more detailed view of purge diffuser **405** of FIG. **4**. Purge diffuser **405** includes four (4) tubes **903***a*-**903***d*, each with a series of holes for dispersing purge hydrogen. In the illustrated embodiment, purge diffuser **405** receives purge hydrogen from needle valve **902** through a *A*;2" tube and hose and each tube **903** comprises a ⅜" tube with twelve (12) 5⁄64" holes. Tubes **903***a*-**903***d* are supported by a frame **904** and protected by a cover plate **905**.

Power modules **201***a* and **201***b* operate as the prime energy source for moving hydrogen hybrid locomotive **100**, as well

as the source for charging the batteries. Generally, DC to DC converter **203**, which is preferably a boost/buck converter, ensures that the correct power and voltages levels are delivered by bus system **207** (FIG. **2**) from power modules **201***a* and **201***b* to the various subsystems. DC to DC converter **203**.

A system controller determines a power set-point in response information characterizing the operation of hydrogen hybrid locomotive **100** and sets the operating points for BOP subsystems **404**, including air system **500** and coolant system **600**, as well as the power output of DC to DC converter **203**.

The voltage from power modules **201***a* and **201***b* varies with the amount of current drawn (e.g. from about 642 to 928 VDC) and DC to DC converter **203** then boosts or bucks the voltage to provide the appropriate level at for the batteries. In addition to the primary power being provided to the batteries and traction motors, power modules **201***a* and **201***b* also power BOP components **404** (the "parasitic loads"). Depending on the operating conditions, for example ambient air temperature and altitude, these parasitic loads can represent between 20 and 30% of the overall required power.

In hydrogen hybrid locomotive **100**, the current and voltage needs vary greatly; hence, bus system **207** includes several different buses. For example, power plant **400** requires voltages of 600 VDC, 350 VDC, 24 VDC, 12 VDC, and 5 VDC. Inverters provide 230 VAC for both primary coolant pump motor **603** and radiator fan motors **602** and **608**.

A high-voltage bus which carries a voltage that varies from about 580 to about 750 VDC, powers traction motors **209***a*-**209***d* and charges the batteries. A **350**V bus supplies power for the air compressor motor and inverters, and 12 VDC and 24 VDC buses are used to power valves, actuators, control systems, and sensors. The locomotive battery provides backup power to the control system when power from power modules **201***a* and **201***b* is not available.

Generally, central control of power modules **201***a*-**201***b* and BOP **404** is implemented through a system of instrumentation, actuators, motor controllers and a programmable automation controller (PAC). (PAC **1700** is discussed further below in conjunction with FIG. **17**).

During normal operation, the PAC receives a power set-point from the locomotive controller. The PAC relays this power set-point to the dc/dc converter **203** controller, as well as establishes the conditions necessary for the power plant **400** to generate the requested power through a combination of open-loop and closed-loop control.

The PAC first calculates the mass air flow rate required by power modules **201***a* and **201***b* to produce the requested power. This calculation is used to command air compressor **502** of air system **500**. PAC then makes small air mass flow rate corrections based on the actual air mass flow delivered to power modules **201***a* and **201***b*.

The PAC also measures the current draw to air compressor **502** for use in estimating the amount of cooling required from cooling system **600**. Small corrections to the speed of primary cooling pump **603** of coolant system **600** are made by measuring the coolant temperatures. If sufficient air is provided, the hydrogen supply is consumed at a rate proportional to the current drawn from the power modules **201***a*-**201***b*.

Unsafe or abnormal conditions in power system **400** are monitored by the PAC. Upon detection of such an anomaly, PAC can either prompt a power reduction or even a full shutdown of power plant **400**. The status of power plant **400**, including the presence of system faults, are provided on user-interface display **208***b* (FIG. **2**). Key fault conditions are also transmitted to the locomotive controller.

As discussed above, the main power source for charging locomotive battery pack **205** is a pair of electrically parallel fuel cell-based power modules **201***a* and **201***b*. In the preferred embodiment, each module **201** contains six fuel cell stacks, and each stack contains 160 cells for a total of 960 cells. Power modules are **201** supplied with reactants (hydrogen and air) as well as coolant (de-ionized water and glycol mixture, i.e. WEG or DiGly) and produce high voltage electricity (500 to 1000 VDC). This electrical power is used to replenish battery pack **205** via DC-DC Converter **203**.

In order to maintain effective system operation, many process flows, temperatures, and pressures are controlled. Most of these variables are conditions which are supplied to the power module stacks of power modules **201**. Air system **500**, described above, performs active air flow control with variable speed air compressor **502**, as well as stack inlet air pressure control with turbocharger **504**. The air temperature in the stack is controlled by the coolant flow rate.

Hydrogen flow within power modules is controlled by stack fuel consumption, jet pump solenoids and opening of purge valves. Hydrogen pressure is controlled with pressure regulators, which are referenced to the air pressure in the stacks.

The coolant flow rate is controlled using primary coolant pump **603**, which circulates flow through parallel loops for the power module stacks, the air system intercooler **503**, and a filter. Coolant pump **603** is responsible for maintaining the differential temperature across the stacks.

Power module **201** inlet temperature is controlled by the radiator bypass valve **604***a*, and the radiator outlet temperature is controlled by radiator fans **602**. Ideally radiator fans **602** are run at minimum speed and coolant is passed through or bypassed around the radiators **601** to maintain stack inlet temperature. Coolant pressure control is passive and is based upon the coolant pump speed.

High level control functions for the locomotive are divided between a locomotive controller and a power system controller. The locomotive controller is responsible for monitoring the state of charge of batteries **205**. The power system controller is responsible for providing the electrical power necessary to charge batteries **205** and provide supplemental traction power during periods of high demand. DC-DC converter **203** delivers the power module **201** power at the voltage of locomotive battery bus **207**. The locomotive controller specifies a power requirement and the power system controller establishes the necessary balance of plant conditions necessary for the fuel cell to produce the requested power.

The control system also includes an emergency shutdown pushbutton at the operator's station, which allows immediately shutdown all power system **401** equipment. This button operates independently of the user interface and fuel cell controllers (i.e. it is hardwired). Hydrogen sensors installed in the rear engine compartment containing power system **401** and the hydrogen storage hoods are hardwired into the emergency stop circuit. An elevated hydrogen level will cause these sensors to initiate an emergency stop.

As discussed above, a single electric motor driven variable speed compressor **502** is used in air system **500** to provide air to both of the power modules **201***a* and **201***b*. Accurate air flow is important because if too much air is forced through the stacks of power modules **201** for a given air pressure and current, the cell membranes may begin to dry out and water balance may not be achieved. If too little air is forced through the stacks, there is increased risk of flooding the stack and the stack voltage will be low and cell voltages will not be stable.

The amount of oxygen a fuel cell stack consumes is directly proportional to the current supplied by the stack. Therefore,

the current demanded can be used to determine the amount of air flow necessary to provide the correct amount of oxygen.

In the illustrated embodiment, there is a 3.39 mechanical speed ratio between the air compressor motor of air compressor **502** and the air compressor itself. In other words, the air compressor rotates 3.39 times faster than the air compressor motor.

The compressor control algorithm is generally shown in FIG. **10**, and is executed by the PAC on the following input and output variables. A gross power request from the locomotive controller is used to calculate how much air from air system **500** is required to meet the locomotive demand and the required BOP **404** power. The control algorithm also accurately controls air stoichiometry of power modules **201** based on individual module currents and determines air set points from a lookup table.

The compressor control outputs are:

1. Compressor motor speed command; and
2. Compressor motor torque command.

The compressor control inputs are:

1. Power module **201***a* stack air mass flow rate;
2. Power module **201***b* stack air mass flow rate;
3. Power module **201***a* current output transducer;
4. Power module **201***b* current output transducer;
5. Power module **201***a* stack inlet temperature;
6. Power module **201***b* stack inlet temperature;
7. Gross power requested by locomotive controller;

In the Start-up Mode, a startup purge of the power module **201** stacks is performed by setting the compressor motor speed command to 750 RPM, such that air compressor **502** runs at 2543 RPM, with a compressor torque command of 20% for 10 seconds.

In the run mode, a Run Mode control algorithm is executed, which performs the following:

1. Calculates the current required to achieve the power requested by the locomotive controller;
2. Calculates the stoic set-point required for the given current;
3. Performs open loop control of air compressor motor speed command based on air flow required;
4. Performs PID (with proportional derivative controller (PID)) closed loop control of the air compressor motor speed command based on measured air flow; and
5. Sets the motor compressor torque command to 20%.

At Block **1000**, for the preferred embodiment of hydrogen hybrid locomotive **100**, the current required to generate the requested gross power is calculated. The requested gross power is calculated in the Power Management algorithm discussed below

The stoic setpoint is determined as follows (Block **1001**, FIG. **10**). First, a current set setpoint is calculated for each power module **201** that is half of the total current setpoint. Then, a stoichiometric ratio is determined for each power module stack, namely, Stoichiometric Ratio A and Stoichiometric Ratio B, based on the characteristics of the fuel cell stacks being used, which in this case are Ballard MK902 fuel cell stacks. In addition, the measured stack currents are used to determine the estimated actual stoic ratio for each stack.

The stoic set-points are modified by purge and cold operation factors, also depending on the type of fuel cell stacks used. The modified stoic setpoints are limited based on the corresponding stack current.

The air compressor control algorithm includes open-loop (Block **1002**, FIG. **10**) and closed-loop portions (Block **1003**, FIG. **10**). The open-loop portion calculates the amount of power module air flow mass required from the stoic setpoints for each power module **201***a* and **201***b*, the number of cells within each power module stack, and a stack air constant, which is also a function of the type of fuel cells being used.

Both the desired mass flow and actual mass flow values are calculated. The actual mass flows are used in the stoic valves associated with power modules **201** to balance air flow through the stacks.

Given that the air flow is directly proportional to compressor speed, the motor and compressor speeds for air compressor **502** is directly calculated from the required air flow and the desired torque.

The closed-loop portion of the air compressor control algorithm calculates a correction amount via a slow proportional integral derivative (PID) in PID Block **1003** with a range limited to +/−100 RPM. The error is calculated so that an increase in error creates a negative response.

In actual embodiments, of hybrid locomotive **100**, final tuning constants are determined in the field.

In the shut-down mode, a shutdown purge is performed by setting the air compressor speed to 750 RPM (air compressor **502** will run at 2543 RPM) and the air compressor motor torque to 10%.

Power modules **201***a* and **201***b* are each associated with an external butterfly (stoic control) valve **1100***a*-**1100***b* at the air outlet, for balancing the air flow through two power modules as shown in FIG. **11**A. Preferably, only one valve is ever commanded to move at a time, and then only in the shut direction. These two valves are decoupled from the air compressor motor controls.

The stoic balancing valve control algorithm balances the air flow between power modules **201***a* and **201***b* and clamps the PWM duty cycles between 5% and 50%. The outputs from the stoic valve control algorithm are:

1. Power module **201***a* Independent Stoic Control Valve position; and
2. Power module **201***b* Independent Stoic Control Valve position.

The inputs operated on by the stoic valve control algorithm are:

1. Measured Power Module **201***a* air mass flow;
2. Measured Power Module **201***b* air mass flow;
3. Power Module **201***a* air flow setpoint (calculated above);
4. Power Module **201***b* air flow setpoint (calculated above).

In the start up and shut down modes, stoic control valves **1100***a*-**1100***b* are completely open. This means that their open commands (MOVA, MOVB) are set to 90%, in the illustrated embodiment.

During run mode, the following open loop control is performed, as illustrated in the flow chart of FIG. **11**B, Blocks **1101**-**1103**.

First the Power Module **201***a* mass flow setpoint ratio is calculated. If this value is less than 0.5, the valve will start to close (Block **1101**):

$$\text{Air Mass Flow Ratio } A = \text{Air Mass Set Point } A / (\text{Air Mass Set Point Total})$$

Second, the Power Module **201***b* mass flow setpoint ratio. If this value is less than 0.5, the valve will start to close:

$$\text{Air Mass Flow Ratio } B = \text{Air Mass Set Point } B / (\text{Air Mass Set Point Total})$$

Third, the valve open loop position is determined for each power module **201***a*-**201***b* (Valve A Open Loop Position and Valve B Open Loop Position) at Block **1103** using the curve provided as FIG. **11**C.

Closed-loop control is implemented for each by executing a PID loop for each stoic balancing valve as shown in the flow chart of FIG. **11**B, Blocks **1104**-**1106**.

1. Setpoint for Power Module **201***a* is input (Block **1104**): Air Mass Flow Ratio A
2. Setpoint for Power Module **201***b* is input (Block **1104**): Air Mass Flow Ratio B
3. Process variable for Power Module **201***a* is calculated (Block **1105**): Air Mass Flow Process Variable A=Air Mass Flow A/(Air Mass Flow A+Air Mass Flow **8**). (A value less than 0.5 means the valve will start to close.)
4. Process variable for Power Module **201***a* is calculated (Block **1105**): Air Mass Flow Process Variable A=Air Mass Flow B/(Air Mass Flow A+Air Mass Flow B). (A value less than 0.5 means the valve will start to close.)
5. PID Output for Power Module **201***a* is generated (Block **1106**): Air Mass Flow A Corrected.
6. PID Output for Power Module **201***b* is generated (Block **1106**): Air Mass Flow B Corrected.

The total command PWM on/off times are then calculated according to the block diagram of FIG. **11**B; Blocks **1107**-**1108**.

1. Total valve command for Power Module **201***a* is calculated as (Block **1107**):

Valve *A* Command=Valve *A* Open Loop Position+Air Mass Flow *A* Corrected.

2. Total valve command for Power Module **201***b* is calculated (Block **1107**):

Valve *B* Command=Valve *A* Open Loop Position+Air Mass Flow *A* Corrected.

3. The PWM on/off times are calculated for each valve (uSec) (Block **1108**).

The command is scaled from a range of 0-100 to 0.5-1. The off and on times are then calculated using the PWM (pulse width modulation) frequency:

Turn Off PWM *A*=(scale(*MF_A*,0,0.5,0.5,0.95)* (1/Freq)*1000000

Turn On PWM *A*=(1−scale(*MF_A*,0,0.5,0.5,0.95))* (1/Freq)*1000000

Turn Off PWM *B*=(scale(*MF_B*,0,0.5,0.5,0.95))* (1/Freq)*1000000

Turn On PWM *B*=(1−scale(*MF_B*,0,0.5,0.5,0.95))* (1/Freq)*1000000

As discussed above in conjunction with coolant system **600**, radiators bypass valves **604***a* and radiators outlet valve **604***b* allow radiators **601** to be bypassed. During normal operation, radiator outlet valve **604***b*, at the outlet of radiators **601** is completely open and bypass valve **601***a* is then controlled to maintain the inlet temperature to power modules **201**. The advantage of this system is that the speed of radiator fans **602**, which presents a large parasitic load, can be minimized while still allowing for additional cooling capacity in the event of a sudden increase in power.

The radiator bypass control algorithm is shown in the flow chart of FIG. **12**. The radiator bypass control outputs are:

1. Radiator bypass valve **604***a* position; and
2. Radiators outlet valve **604***b* position. The radiator bypass control inputs are:

1. Primary coolant pump **603** outlet temperature;
2. Radiators **601** outlet temperature;
3. Power module **201***a* inlet temperature; and
4. Power module **201***b* inlet temperature.

The radiators bypass control ensures that the power module **201***a*-**201***b* inlet temperatures are controlled to their setpoint of 65 C. Additionally, the algorithm ensures that radiator bypass valve **604***a* and radiator outlet valve **604***b* fail in the open position in order to prevent radiator damage if primary coolant pump **603** is running or is started.

In the shut down mode, a determination is made as to whether the system is "waiting to warm up." If the system is in warm up, then radiator bypass valve **604***a* and radiator outlet valve **604***b* are set to Position A, in which radiator bypass valve **604***a* is by default 95% open and radiator outlet valve **604***b* is by default 15% open. Otherwise, radiator bypass valve **604***a* and radiator outlet valve **604***b* are set to Position B, in which radiator bypass valve **604***a* is by default 20% open and radiator outlet valve **604***a* is by default 95% open) (i.e. the fail safe position, provides cooling in case a valve fails).

In the start up mode, radiator bypass valve **604***a* and radiator outlet valve **604***b* are set to their start up positions, in which radiator bypass valve **604***a* is set by default to 95% open and radiator outlet valve **604***b* is set by default to 5% open. These start up settings ensure that no heat is lost to the radiators **601** during start up.

In the run mode, the power modules **201** inlet temperature setpoints are set to 65 C (Block **1201**). Then, if the average of the inlet temperatures to power modules **201***a* and **201***b* is below 62 C (Block **1202**), then the Warmed Up flag is set to FALSE (Block **1204**), otherwise the Warmed UP flag set to TRUE (Block **1203**). (Once the Warmed Up flag is set TRUE, it is not set back to FALSE).

The open-loop portion of the valve control algorithm then proceeds as follows. If Warmed Up flag is false (Block **1205**) then radiator outlet valve **604***b* is set to fully shut (Block **1206**). Otherwise, if the Warmed Up flag is TRUE at Block **1205**, radiator outlet valve **604***b* is set to the run position at Block **1207**, which defaults to 100% open. In the illustrated embodiment, the movement of radiator outlet valve **604***b* is limited 100%/min.

The bypass valve **604***a* portion of the algorithm includes both open-loop and closed-loop portions. (The open loop portion provides fast and relatively accurate control and the closed loop portion corrects any residual error.)

The open loop portion uses temperature data from the radiators **601** inlet and the radiators **601** outlets to calculate a valve position which would be required to meet the power inlet temperature set point (i.e. 65 C in default). If at Block **1208** the radiator **601** inlet temperature is less than the power module **201** inlet temperature setpoint (no cooling is needed), then radiator bypass valve **604***a* is fully opened (Block **1209**). Once the power modules have warmed up and the radiators inlet temperature is greater than the power module inlet temperature set (cooling is required), the radiator bypass valve **604***a* starts to close (Block **1210**). The open loop sub-procedure (Block **1211**) is preferably:

IF Primary Coolant Pump **603** outlet temperature (Primary Coolant Pump Temp)>=stack inlet temperature setpoint (Stack Inlet Temp. Setpoint) THEN

Open Loop Bypass Valve Setpoint=

Open Loop Bypass Valve Max. $-\left(\frac{\text{Primary Coolant Pump Temp} - \text{Stack Inlet Temp Setpoint}}{\text{Primary Coolant Pump Temp} - \text{Radiator Outlet Temp}}\right)100$

ELSE

Open Loop Bypass Valve=Open Loop Bypass Valve Max.

Open Loop Bypass Valve Max. defaults to 95%.

The closed loop portion (Block **1212**) uses power module **201** inlet temperature as closed loop to a regular PID routine

in order to compensate for any steady state error. In particular, the closed loop portion is given by a PID, with a previous value that is the previous CV, not the actual valve output. The PID error value is calculated as:

Error=Stack Inlet Temp. Setpoint−Average of Power Module 201*a* and 201*b* Inlet Temperatures

The PID gains for the illustrated embodiment are as follows:

Kp = 0.75	[%/C]
Ki = 0.02	[1/sec]
Kd = 0.0	[sec]

The valve command is (clamped between 0 and 100%):

Outlet Bypass Valve Command=Open Loop Bypass Valve+Error

A dead band is applied to the valve command to prevent unnecessary valve chattering and wear. So that radiator bypass valve **604***a* can move to its minimum and maximum commands, the dead band is not applied when the valve is near its minimum and maximum commands.

As previously discussed, radiator fans **602** are used to control the radiators **601** outlet temperature. Generally, open loop control is used to set the approximate fan speed needed for the current heat load and closed loop control is used to compensate for any steady state errors. A preferred fan speed control algorithm is described in the flow chart of FIG. **13** for the run mode.

The outputs generated by the speed control algorithm are:

1. Radiator fan speed for both fans **602**;
2. Radiator fan run command; and
3. Rear hood louvers open command.

The inputs operated on by the fan speed control algorithm are:

1. Radiator **601** coolant output temperature in C;
2. Stack Heat Load;
3. Rear hood louvers position limit switch; and
4. Rear hood hydrogen detector.

The fan speed control algorithm controls radiator **601** outlet temperature to 62 C, maintains a fan minimum speed of 400 RPM, an maintains a fan maximum speed of 1800 RPM. Additionally, this algorithm opens the rear hood louvers if the fans are running or if an elevated hydrogen level is detected in the read hood.

In the shutdown mode, the fan speed is set to 0% and the Warmed Up flag is set to FALSE. If the rear hood hydrogen detector AT is greater than 25%, the rear hood louvers open command is activated to open the louvers.

In the start up mode, the open loop fan speed is set to 400 RPM, the Warmed Up flag is set to FALSE, and the open louvers command is activated to open the louvers.

In the run mode, if the radiator coolant output temperature is less than 62 C (Block **1301**), then the Warmed Up flag is set to FALSE (Block **1302**), otherwise the Warmed Up flag is set to TRUE (Block **1303**). (Once the Warmed Up flag is set to TRUE, it is not set back to FALSE. This flag is the same flag described in FIG. **12** for the radiator bypass valve control algorithm.)

During open loop control, if at Block **1304** the Warmed Up flag is FALSE, then the fan open loop speed is set to 400 RPM at Block **1305**. Otherwise, at Block **1306**, the open loop fan speed is determined based upon the power module heat load by linearly interpolating using the following table:

Heat Load (kW)	Open Loop Fan Speed (RPM)
40	200
75	400
150	800
300	1700
340	1700

During close loop control, if the Warmed Up command is false at Block **1307**, the PID algorithm is reset at Block **1308** to prevent it from winding up the fan speed as the system comes up to temperature and closed loop fan speed is set to zero. Otherwise a correction for deviation from the radiator outlet temperature set point (defaults to 62 C), is determined by applying a PID at Block **1309**. This PID is a slowly responding controller that is mainly for steady state error elimination, not for active transient correction. The initial controller gains are:

P=2

I=0.01%

D=0

The final fan speed command is then (Block **1310**):

Fan Speed=Open Loop Fan Speed+Closed Loop Fan Speed.

The fan speed is limited to a maximum of 1800 RPM. A dead band (1.5%) is applied to the fan speed command to minimize unnecessary RPM changes. So that fans **602** can run at their minimum and maximum speed, the dead band is not applied when the fans are near their minimum and maximum speed (within 5%).

The open louvers command is activated to open the louvers (Block **1311**).

In the shutting down mode, fans **602** run at **400** RPM and the louvers are open.

A more detailed diagram of DC to DC converter **203** is provided as FIG. **14**. The overall power management system is shown in FIG. **15**.

During startup, power is drawn from the batteries and delivered to balance of plant **404**. Once power modules **201***a* and **201***b* are up and running, power is drawn from power modules **201***a* and **201***b* and delivered to both the batteries **204** and balance of plant **404**.

As shown in FIG. **14**A, DC to DC converter **203** includes three (3) converter subsystems **1400***a* (Converter A), **1400***b* (Converter B), and **1400***c* (Converter C). In the preferred embodiment, each converter subsystem **1400** consists of set of American Superconductor PM1000 power conversion modules.

CAN communication, though the AmsCAN, v1.1, protocol is used to communicate with each converter subsystem **1400**. Each converter subsystem is assigned a unique address.

Power modules **201***a* and **201***b* are used as a battery charger but exhibit a characteristic voltage droop as the current drawn from them increases. On the other hand, the batteries require a specific voltage/current profile during charging. As a result DC-DC Converter B, which couples to the locomotive battery bus, is commanded to follow this profile by the power module controller, regardless of the actual voltage being produced by power modules **201**.

The inputs and the outputs to the DC to DC converter control algorithm are as follows.

For Converter A the commands and control messages include:

1. Converter A Command Request (Run=0, Stop=1);
2. Converter A Parameter Write: Mode, output voltage set point.

For Converter B the commands and control messages include:

1. Converter B Command Request (Run=0, Stop=1);
2. Converter B Parameter Write: Mode, output voltage set point; and buck reference set point, and buck output voltage set point.

For Converter C the commands and control messages include:

1. Converter B Command Request (Run=0, Stop=1).
2. Converter C Parameter Write Mode, buck output voltage setpoint.

The unsolicited inputs include State Change, Fault Report, and Warning Report.

The hard inputs include locomotive battery bus voltage, locomotive battery bus current draw, BOP bus voltage, and BOP bus current draw.

The soft inputs include Net Power Available, which is the net power available from power modules **201** based on the current air mass flow rate, calculated in the Power Management algorithm discussed below.

The DC to DC converter control algorithm implements a number of functions. Among other things, this algorithm transfers the specified electrical power from the power modules **201** to the batteries. It also provides power for the balance of plant equipment during power plant startup and ensures that the voltage on the battery bus does not exceed the specified maximum. Additionally, the DC to DC control algorithm interprets and responds to DC-DC Converter faults and ensures that power is available at the output of Converter B in order to run the converter modules.

The DC to DC converter control algorithm is set out in the following table:

As described in the table, upon entering Shutdown Mode, Converters A, B, and C are all commanded to stop. After which, while in the shutdown mode, DC to DC converter **203** is monitored for Unsolicited Reports.

Upon entering the start up mode, the output voltage set point for Converter B (DC to DC Output Voltage Setpoint) is set to 1000 VDC, the Converter B write mode is set to 0, and Converter B is commanded to run.

The Buck output voltage set point for Converter C is set to 350 VDC and the write mode for Converter C is set to 1.

During the startup mode, DC to DC converter **203** is monitored for Unsolicited Reports.

Upon entering the run mode, the Converter A output voltage set point (DC to DC Output Voltage Setpoint) is set to 1050 VDC, the write mode is set to 0, and Converter A is commanded to run. The write mode for Converter B is set to 1.

While in Run Mode, a PID control algorithm is run to account for errors in the current regulation in Converter B. In the preferred embodiment, the PID algorithm:

1. Calculates the current setpoint as:

Net Current Available=Net Power Available/Battery Bus Voltage;

2. Uses the Process Variable: Battery Bus Current Draw;
3. Generates output=Current Correction; and
4. Uses the PID Parameters:
   P: 0.1/A
   I: 1/sec
   D: disabled

The output of the PID correction is added to the current setpoint to obtain the final current set point

Final Current Setpoint=Net Current Available+Current Correction

The final current set point (Final Current Setpoint) is written to BUCKPosIRefLim for Converter B.

	Converter			
System Mode	A (Fuel cell Input)	B (Battery In/Out)	C (Medium Bus Voltage Out)	Power Flow
Shutdown	Stop Mode	Stop Mode	Stop Mode	None
Startup	Stop Mode	Run Mode, Boost, Regulate Vbus_16 to 1000 VDC (Output Voltage Setpoint = 1000, Mode = 0)	Run Mode, Buck, Regulate Vbuck_16 to 350 VDC (Buck Output Voltage = 350, Mode = 1)	From Locomotive Battery Bus to Medium Voltage Bus
Run	Run Mode, Boost, Regulate Vbus_16 to 1050 VDC (Output Voltage Setpoint = 1050, Mode = 0)	Run Mode, Buck, Regulate IoutFbk to Current needed to produce power setpoint at voltage of Battery Out (Buck Output Voltage = set to maximum voltage allowed on batt bus, take out = current setpoint, Mode = 1)	Run Mode, Buck, Regulate Vbuck_16 to 350 VDC (Buck Output Voltage = 350, Mode = 1)	From Fuel cell Bus to Battery Bus, From Fuel cell Bus to Medium Voltage Bus
Shutting Down	Run Mode, Boost, Regulate Vbus_16 to 1050 VDC (Output Voltage Setpoint = 1050, Mode = 0)	Run Mode, Boost, Regulate Vbus_16 to 1000 VDC (Output Voltage Setpoint = 1000, Mode = 0)	Run Mode, Buck, Regulate Vbuck_16 to 350 VDC (Buck Output Voltage = 350, Mode = 1)	Initially, power flow is from the Fuel cell Bus to the Medium Voltage Bus but then flows from the Battery Bus to the Medium Voltage Bus

The value for the maximum allowable voltage allowed on the battery bus becomes the back output setpoint for Converter B.

During the run mode, DC to DC converter **203** is monitored for Unsolicited Messages.

Upon entering Shutting Down Mode, a O is written as the Mode for Converter B. In the Shutting Down Mode, DC to DC converter **203** is monitored for Unsolicited Reports.

The power management algorithm dynamically adjusts for variations in the balance of plant **404** power consumption and limits the DC-DC converter set points based upon available air mass flow. The power management algorithm illustrated in the flow chart of FIG. **15**.

The power management algorithm generates the following outputs:

1. Gross power setpoint used above in the main air compressor algorithm; and
2. Net power setpoint used above in the DC to DC converter algorithm.

The power management algorithm inputs include:

1. Power request either from locomotive or from HMI;
2. Power module **201***a* air mass flow;
3. Power module **201***b* air mass flow;
4. Ambient air temperature;
5. BOP **404** bus voltage;
6. BOP **404** current draw; and
7. Power factor. (The power factor reduces maximum allowed power, not the desired power, during times when an operating parameter is not within acceptable bounds.)

The power management algorithm limits a gross power request based upon any power factors in place or a warm up condition. This algorithm also raises or lowers the net power module **201** power setpoint in order to meet the locomotive power demand and balance of plant **404** power consumption. The power management algorithm also limits the power drawn by Converter B of DC to DC Converter **203** based upon available air mass flow.

In both the shutdown and startup modes, Gross Available Power is set to 10 kW and Net Power Available to 0 kW.

The run mode is described in detail in FIG. **15**, but generally consists of the following steps. First, the gross power required by the locomotive is calculated. Second, a determination is made as to how much power the current air mass flow will support (i.e. the power available). Third, the power available is subtracted from the gross power required to calculate the net power available. This power is used as the setpoint to DC-DC Converter B.

In the flow chart of FIG. **15**, the gross power allowed is calculated based on whether the system is Warmed UP (Block **1501**), as determined by calculations in the radiator bypass and outlet valve control algorithms discussed above.

If not warmed up at Block **1501** THEN

Maximum Allowable Power=90 kW (Block **1502**)

ELSE

Maximum Allowable Power=Power Factor*Default Maximum Allowable Power (Block **1503**)

Gross Allowable Power=MIN(Maximum Allowable Power,Requested Power) (Block **1504**)

Where the maximum Maximum Allowable Power defaults to 230 kW

The gross power available based upon the current air mass flow is the calculated, by first calculating the available current for each power module **201** (Block **1505**):

Current Available Power Module 201*a*=Air Mass Flow *A*/(Stoichiometric Ratio *A***K*)

Current Available Power Module 201*b*=Air Mass Flow *B*/(Stoichiometric Ratio *B***K*)

Where K is a constant related to the number of cells in the power module stack and an air constant characterizing the particular fuel cell stacks used, for example, Ballard MK902 fuel cell stacks.

The total available current is calculated (Block **1506**) as:

Total Current Available=Current Available Power Module 201*a*+Power Available Power Module 201*b*

The gross available power module power (Gross Available Power) is calculated at Block **1507** based upon the stack polarization curve for the type of fuel cells used:

Gross Power Available=*A**(Total Current Available)^2+*B**(Total Current Available)+*C* [kW]

Where A, B, and C are constants based on the polarization curve for the type of fuel cell stack.

The net power available based upon the current mass air flow, is calculated (Block **1508**) by subtracting off the power needed for balance of plant **404**. This will be the setpoint to DC-DC converter **203** that delivers power to the battery bus (DC-DC Converter B).

Net Power Available=Gross Power Available

In the illustrated embodiment of hydrogen hybrid locomotive **100**, three methods are used to determine the amount of hydrogen fuel available for power modules **201***a* and **201***b*: (1) monitoring the pressure in the hydrogen storage tanks **204** while running; (2) calculating the mass of the hydrogen consumed by power modules **201**; and (3) calculating the mass of the hydrogen in the storage tanks. The amount of hydrogen lost to purging is calculated by subtracting the hydrogen consumed by power modules **201** from the change in weight of the hydrogen in the storage tanks.

The outputs generated by the fuel gage algorithm are:

1. Fuel Level—current amount of hydrogen fuel available in barG;
2. H2 Consumption—hydrogen consumed by power modules **201** in kg; and
3. H2 Weight—current weight of the hydrogen in the storage tanks.

The inputs to the fuel gage control algorithm are:

1. Rear bank of hydrogen tanks **300***a* pressure transmitter;
2. Front bank of hydrogen tanks **300***b* pressure transmitter;
3. Power module **201***a* current transmitter;
4. Power module **201***b* current transmitter;
5. Rear bank of hydrogen tanks **300***a* temperature transmitter; and
6. Front bank of hydrogen tanks **300***b* temperature transmitter.

While the power modules **201***a* and **201***b* are running, the fuel gage indicates to the operator, presented on display **208***b*, the current fuel available, the hydrogen consumed, and the current weight of the hydrogen in the storage tanks. The fuel gage also records the hydrogen pressure upon shutdown, since when power modules **201** are not running, the front and rear bank hydrogen pressure transmitters are isolated from the tanks they measuring. The fuel gage algorithm additionally records the hydrogen weight in the storage tanks upon shutdown, since when power modules **201** are not running, the front and rear hydrogen bank temperature sensors, as well as the front and rear hydrogen bank pressure transmitters, are isolated from the tanks they measuring.

In both the shutdown and startup modes, the fuel gage algorithm reads the previously recorded hydrogen fuel level from disc and reports it as the current fuel level. The previ-

ously recorded fuel weight and the previously recorded starting fuel weight are also read from disc and respectively reported as the current weight and the starting weight.

The fuel gage run mode is illustrated in the block diagram of FIG. **16**. The minimum of the hydrogen bank pressure readings (i.e. front and back pressure transmitter readings) is recorded to a disc every 1 minute and the minimum is reported as the current fuel level on display **208***b* every 1 second (Block **1601**).

The cumulative hydrogen consumed by the power modules **201** is calculated and saved to disc every 1 min. This calculation is reported as the current hydrogen consumed every 1 second (Block **1602**). The hydrogen consumed by each power module is:

$$N = \frac{I_{stack} \times N_{cell}}{F \times N_{e^-/molecule}}$$

N=reactant flow rate, gmol/s

F=Faraday's constant, 96,485.3 coulomb/gmol

$N_{e^-/molecule}$=number of electrons transferred per molecule . . . =2 for H_2

This calculation is made for both power modules **201**, the results are added together, and a running total kept.

The current hydrogen weight in the storage tanks calculated, saved to disc every 1 min, and reported as the current hydrogen weight every 1 second (Block **1603**). The current hydrogen weight is:

$$m = \frac{P * V * mw}{R * T}$$

Where:

m=mass in grams

P=pressure in ATM

V=volume (2870 L)

mw=molecular weight of hydrogen (2.02 g/mol)

R=ideal gas constant (0.08206(*L**ATM)/(*K**mol))

T=temperature in *K*

FIG. **17** is a block diagram illustrating the PAC **1700** architecture, which executes the algorithms discussed above. PAC **1700** is based on a conventional computer (hardware) processing system and interfaces with the locomotive controller, sets to modes of the various subroutines, and contains the logic hardware necessary to implement system start up, run, and shutdown sequences.

FIG. **17** executes various algorithms, including the air compressor, stoic balancing valves, radiator bypass, radiator fans, dc to dc converter, power management, and fuel gage control algorithms discussed above as corresponding subroutines **1701**.

PAC **1700** also maintains an input/output table, which provides an interface between subroutines **1702** and with inputs and outputs **1703**. Inputs and outputs **1703** provide the physical interface with the systems described above.

The principles of the present invention discuss above allow for the design and construction of practical railroad locomotives driven by a fuel cell-battery hybrid propulsion system. Such railroad locomotives are robust, and will withstand the harsh operating environments experienced during everyday use in a typical rail yard. At the same time, the use of hydrogen addresses many, if not all, of the problems related to the use of fossil fuels found in conventional diesel electric locomotives.

Although the invention has been described with reference to specific embodiments, these descriptions are not meant to be construed in a limiting sense. Various modifications of the disclosed embodiments, as well as alternative embodiments of the invention, will become apparent to persons skilled in the art upon reference to the description of the invention. It should be appreciated by those skilled in the art that the conception and the specific embodiment disclosed might be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims.

It is therefore contemplated that the claims will cover any such modifications or embodiments that fall within the true scope of the invention.

What is claimed is:

1. A hydrogen hybrid locomotive comprising:

a set of batteries for driving a plurality of electric traction motors for moving the locomotive along a set of railroad rails; and

a fuel cell power plant for charging the set of batteries and driving the electric traction motors, the fuel cell power plant comprising:

at least one fuel cell power module for generating electrical current by reacting hydrogen fuel and oxygen from intake air, the amount of electrical current proportional to an air mass flow of the intake air;

an air system for selectively providing an air mass flow to the fuel cell module to generate an amount of electrical current required for corresponding operating conditions of the locomotive; and

a cooling system for cooling the at least one fuel cell power module in response to the amount of current being generated by the at least one fuel cell power module, wherein the cooling system comprises:

a pump for pumping cooling fluid;

a heat exchange system for extracting heat from cooling fluid provided by the pump; and

a valve system for selectively providing cooling fluid from the heat exchange system to the fuel cell power module and for selectively providing cooling fluid from the pump to the fuel cell power module while bypassing the heat exchange system.

2. The hydrogen hybrid locomotive of claim **1**, wherein the fuel cell power module comprises a proton exchange membrane fuel cell.

3. The hydrogen hybrid locomotive of claim **1**, further comprising a mounting frame supporting the fuel cell power module and isolating the fuel cell power module from shock loads in each of lateral, horizontal, and vertical directions.

4. The hydrogen hybrid locomotive of claim **3**, wherein the mounting frame further supports and isolates the air system and the cooling system.

5. The hydrogen hybrid locomotive of claim **1**, further comprising:

a system of busses for providing power to the traction motors and the set of batteries; and

a DC to DC converter for interfacing the fuel cell power module with the system of busses.

6. The hydrogen hybrid locomotive of claim **1**, herein the air system comprises:

a variable speed compressor for providing the air mass flow of a selected pressure to generate the amount of electrical current required; and

a turbocharger disposed between an output of the compressor and an air inlet to the fuel cell power module for providing an additional increase in air pressure and for controlling backpressure, wherein the turbocharger is drive by exhaust from the fuel cell power module.

7. The hydrogen hybrid locomotive of claim **6**, further comprising an intercooler disposed between the outlet of the compressor and an inlet of the turbocharger and receiving cooling fluid from the cooling system.

8. The hydrogen hybrid locomotive of claim **1**, wherein the heat exchange system comprises:

at least one radiator receiving cooling fluid from the pump; and

a least one fan providing air flow across the at leas one radiator.

9. The hydrogen hybrid locomotive of claim **8**, wherein the at least one radiator comprises first and second radiators operating in a two-pass cross-counter flow system.

10. The hydrogen hybrid locomotive of claim **1**, wherein the locomotive is a switcher locomotive.

11. A hydrogen hybrid switcher locomotive comprising:

a set of hydrogen storage tanks;

a set of electrical traction motors for moving the switcher locomotive on a set of rails;

a set of batteries for storing electric power for driving the electrical traction motors;

first and second fuel cell modules for generating electrical power for driving the traction motors and charging the set of batteries, the first and second fuel cell modules generating a demanded amount of electrical power from hydrogen provided by the set of hydrogen tanks and a corresponding air mass flow;

a DC to DC converter and bus system for providing power generated by the first and second fuel cell modules to the traction motors and the batteries;

an air system including a variable speed compressor for providing the air mass flow required by the first and second fuel cell modules to generated the demanded amount of electrical power, comprising:

an intercooler disposed at an outlet of the variable speed compressor, wherein the intercooler receives cooling fluid from the cooling system; and,

a turbocharger disposed between an outlet of the intercooler an air inlet of at least one of the first and second fuel cell power modules for controlling back-pressure;

a cooling system including a heat exchanger system and bypass valves for selectively providing cooling fluid to the first and second fuel cell module; and

an isolation system for isolating the first and second fuel cell modules from mechanical stresses during operation of the locomotive.

12. The hydrogen hybrid switcher locomotive of claim **11**, wherein the isolation system further isolates the air system and the coding system from mechanical stresses during operation of the locomotive.

13. The hydrogen hybrid switcher locomotive of claim **11**, wherein the cooling system includes a primary heat exchanger loop for removing heat from the cooling fluid provided to the first and second fuel cell power modules, the primary heat exchanger loop comprising:

first and second radiators operating as a two-pass cross-counter flow system;

a pump for pumping the cooling fluid output from the first and second fuel cell power modules to the first a second radiators; and

first and second fans providing air flow across the first and second radiators.

14. The hydrogen hybrid switcher locomotive of claim **13**, wherein the primary heat exchanger loop further provides cooling fluid to an intercooler forming a portion of the air system.

15. The hydrogen hybrid switcher locomotive of claim **13**, wherein the cooling system includes a secondary heat exchanger loop for providing cooling fluid to the DC to DC converter, the secondary heat exchanger loop comprising:

a secondary heat exchanger radiator aligned with a selected one of the first and second fans;

a first manifold receiving cooling fluid from the secondary heat exchanger radiator;

a first pump for pumping cooling fluid from the first manifold to the DC to DC converter;

a second manifold receiving cooling fluid output from the DC to DC converter; and

a second pump for pumping cooling fluid output from the second manifold to the secondary heat exchanger radiator.

16. The hydrogen hybrid switcher locomotive of claim **15**, wherein first manifold further provides cooling fluid to the variable speed compressor and the second manifold further receives cooling fluid from the variable speed compressor.

17. The hydrogen hybrid switcher locomotive of claim **15**, further comprising:

a condenser receiving cooling fluid from the first manifold and output cooling fluid to the second manifold; and

a condenser bypass loop including a valve system for selectively bypassing the condenser.

18. The hydrogen hybrid switcher locomotive of claim **11**, further comprising a hydrogen purge system comprising:

a needle valve for controlling hydrogen purged from the first and second fuel cell power modules; and

a diffuser for diffusing hydrogen passed through the needle valve.

19. The hydrogen hybrid switcher locomotive of claim **18**, wherein the diffuser is aligned with an exhaust air stream provided by the codling system.

20. The hydrogen hybrid switcher locomotive of claim **19**, wherein the first and second fuel cell power modules are housed within a hood including a louver system for venting hydrogen out of the housing.

21. The hydrogen hybrid switcher locomotive of claim **11**, wherein the set of hydrogen storage tanks are disposed above the set of batteries.

22. The hydrogen hybrid switcher locomotive of claim **11**, further comprising an adjustable ballast system disposed under a primary locomotive chassis.

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